AD-A047 906 NORTHROP CORP HAWTHORNE CALIF ELECTRONICS DIV F/G 17/7
COMPUTER PROGRAM PERFORMANCE SPECIFICATION. VOLUME I. RADIO NAV--ETC(U)
JUL 73 N00039-73-C-0209

UNCLASSIFIED NORT-73-48-VOL-1 NL

1 OF 3
AD
A047906

AD-A047906

(1)

Northrop Corporation Electronics Division

NORTHROP

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

AD-A047906

(1)

NORTHROP

Electronics Division

☐ This submittal applies to AN/BRN-7 (Submarine Ω) only.

☐ This submittal applies to AN/SRN-( ) (Hydrofoil Ω) only.

☒ This submittal applies to both AN/BRN-7 and AN/SRN-( ).

CONTRACT NO: N00039-73-C-0209

PROGRAM NAME: AN/BRN-7

CDRL No: A01C

Title of CDRL: Computer Program Performance Specification

Title of Doc: Radio Navigation Receiving Set, Omega AN/BRN-7 NORT 73-48

Date: 12 July 1973

Initial Submittal: ☒ | Release | APS 7-13-73

Resubmittal: ☐ | Authentication

Prepared by: Systems Development
Orgn. Name

A4734, Ext. 574
Orgn. No. and Ext.

Approved by:

Norman P. Clark
Supervisor of Preparing Orgn.

Program Mgr.

Proj. Engr./Proj. Mgr.

FORM 6512 (2-72)

NORTHROP

Electronics Division

COPY #

NORT 73-48

COMPUTER PROGRAM
Volume I **PERFORMANCE SPECIFICATION**

Radio Navigation Receiving Set, Omega
AN/BRN-7

Approved by

L. R. Urban, Chief
Systems Engineering Group

CONTENTS

Section		Page
1	SCOPE	1
	1.1 Identification	1
	1.2 Functional Summary	1
2	APPLICABLE DOCUMENTS	5
3	REQUIREMENTS	
	3.1 Introduction	6
	3.1.1 OMEGA Task and System Breakdown	6
	3.2 Functional Description	16
	3.2.1 Introduction	16
	3.2.2 Functional Description and Requirements of OMEGA Hardware	19
	3.2.3 Computer Input/Output	39
	3.2.4 Operation	50
	3.2.5 Detailed System Operations	77
	3.3 Detailed Functional Requirements	88
	3.3.1 Synchronization	88
	3.3.2 Signal Input Timing	98
	3.3.3 Antenna Switching Control	104
	3.3.4 Bias, Scale Factor and Phase Shift Calibration	108
	3.3.5 Noise Estimation (Q_t)	112
	3.3.6 Phantom Calculation Calibration	115
	3.3.7 Burst Phase Measurement	117
	3.3.8 Base Station Selection	120
	3.3.9 Phase Difference Function	122
	3.3.10 Tracking Filters	124
	3.3.11 Combinational Kalman Filter	133
	3.3.12 Propagation Prediction	159
	3.3.13 Velocity and Heading Processing	176
	3.3.14 Navigation	179
	3.3.15 Control-Indicator Panel Requirements	183
	3.3.16 Built-In Test Programs	205
	3.3.17 Built-In Test Equipment	226
	3.4 Adaptation	230
APPENDIX A	MATHEMATICAL ANALYSIS	231

ILLUSTRATIONS

Figure		Page
1.1	Primary Functional Block Diagram of Submarine Omega Computer Program	2
3.1-1	OMEGA Transmitter Locations and Broadcast Pattern	7
3.1-2	First Level Task and System Implementation for OMEGA Navigation	9
3.2-1	Submarine OMEGA Navigation Set Block Diagram	17
3.2-2	Orthogonal Loop Antenna Amplifiers and OMEGA Receiver Block Diagram	21
3.2-3	Antenna Switching Matrix Circuit Simplified Block Diagram	23
3.2-4	Receiver Strip Simplified Block Diagram	25
3.2-5	Correlator and Digital Converter Circuit Simplified Block Diagram	27
3.2-6	Precision Frequency Generator Circuit Simplified Block Diagram	29
3.2-7	Receiver-Computer Interface Circuit Simplified Block Diagram	30
3.2-8	Input/Output Circuit Simplified Block Diagram	32
3.2-9	Control-Indicator Assembly Simplified Block Diagram	37
3.2-10	OMEGA Receiver-Computer Operating Indicator	51
3.2-11	OMEGA Control and Indicator Panel	53
3.2-12	OMEGA Interface Box	63
3.2-13	OMEGA Signal Synchronization	79
3.2-14	Burst Filter Routine Block Diagram	81
3.2-15	Tracking Filter Routine Block Diagram	83
3.2-16	Propagation Prediction Routine Block Diagram	85
3.2-17	Combinational Filter Routine Block Diagram	86
3.3-1	OMEGA Transmission Envolope	89
3.3-2	The Dissymmetry of the Pattern	89
3.3-3	Long and Short Interval Sums	91
3.3-4	Synchronization Attempts	93
3.3-5	Burst Pattern	99
3.3-6	Burst/Slot Segmentation	100
3.3-7	Four-Lobe Loop Antenna Configuration for Ranges of θ_{BR}	106
3.3-8	Conductivity Map	167/168
3.3-9	OMEGA Coordinate System	180
3.3-10	System Azimuthal Relationships	195
3.3-11	System Vector Relationships	196
3.3-12	Typical Switch Matrix	206
3.3-13	Avionic I/O	209
3.3-14	Phase-to-Digital Converter	214
3.3-15	Phase Counter I/O Test	215
3.3-16	I/O-DMA Test	217

ILLUSTRATIONS (CONTINUED)

Figure		Page
3.3-17	Precision Frequency Generator BITE	220
3.3-18	Self-Test BITE in The I/O	227
3.3-19	Computer/System BITE	228
3.3-20	Power Supply Bite	229

TABLES

Table		Page
3.1-1	Characteristics of the AN/BRN-7 Receiver-Computer	11
3.2-1	Summary of RF Amplifier Configuration	24
3.2-2	1070 - Fixed Memory Locations	40
3.2-3	Control and Indicator Panel DMA Image	44
3.2-4a	Display Registers - Characters	
3.2-4b	Display Registers - Punctuation	47
3.2-5	Legend Displays	47
3.2-6	Antenna Select Output Signal Format	49
3.2-7	DMA Test Select Word Format	50
3.2-8	OMEGA Receiver-Computer Indicators	52
3.2-9	OMEGA Control-Indicator Operating Controls and Indicators	54
3.2-10	OMEGA Interface Box Controls and Indicators	62
3.3-1	State Vector Element Meaning	134
3.3-2	Transition Matrix	138
3.3-3	System Noise Matrix	139
3.3-4	Measurement (Extraction) Matrices	147
3.3-5	Disurnal Constants	165
3.3-6	Auroral Constants	166
3.3-7	Values of CAY and DCAY	169
3.3-8	Values of CAY1 and DCAY1	170
3.3-9	Test Select - DMA	224
3.3-10	Antenna Select - DMA	225

SECTION 1

SCOPE

1.1 IDENTIFICATION

This specification describes the performance requirements for the Submarine OMEGA Computer Program used by the AN/BRN-7 OMEGA Navigation Set, which together define the Submarine OMEGA Navigation System. The tape which defines the computer program is entitled AN/BRN-7 SUBMARINE MOD (No.), and is presented in other portions of this documentation.

It will be noted throughout this document that all eight OMEGA broadcasting stations are presumed operating. Although there are only four operating currently the computer program is designed for all eight. Since all operating concepts and criteria apply to four as well as eight operating stations, there should be no confusion.

1.2 FUNCTIONAL SUMMARY

The OMEGA signals are transmitted from land-based stations in a multiplexed pattern on three carrier frequencies. On each frequency the pattern is composed of eight consecutive bursts of energy which repeat every 10 seconds (the OMEGA broadcast cycle). To receive these patterns there are three superheterodyne receivers in the OMEGA hardware, one receiver for each frequency to process each burst of the incoming patterns. The resultant output of each receiver strip is a sine-cosine pair of digital numbers whose values represent a time integration over 5 milliseconds of whatever signal happened to be processed by the receiver during that time. If no signal was present, then the pair represents random noise; if a signal was present, then the pair will represent the sine and cosine of the phase of that signal relative to that of the OMEGA-system crystal oscillator.

Figure 1.1 is a functional block diagram of the computer program. The first requirement is to control the five related pattern-dependent processes with respect to the timing of the incoming burst pattern. This function is represented as 3.3.2 Signal Input Timing and Control. As will be noted, function 3.3.1 Synchronization initially determines this coordination, after which 3.3.2 will maintain the timing for the following:

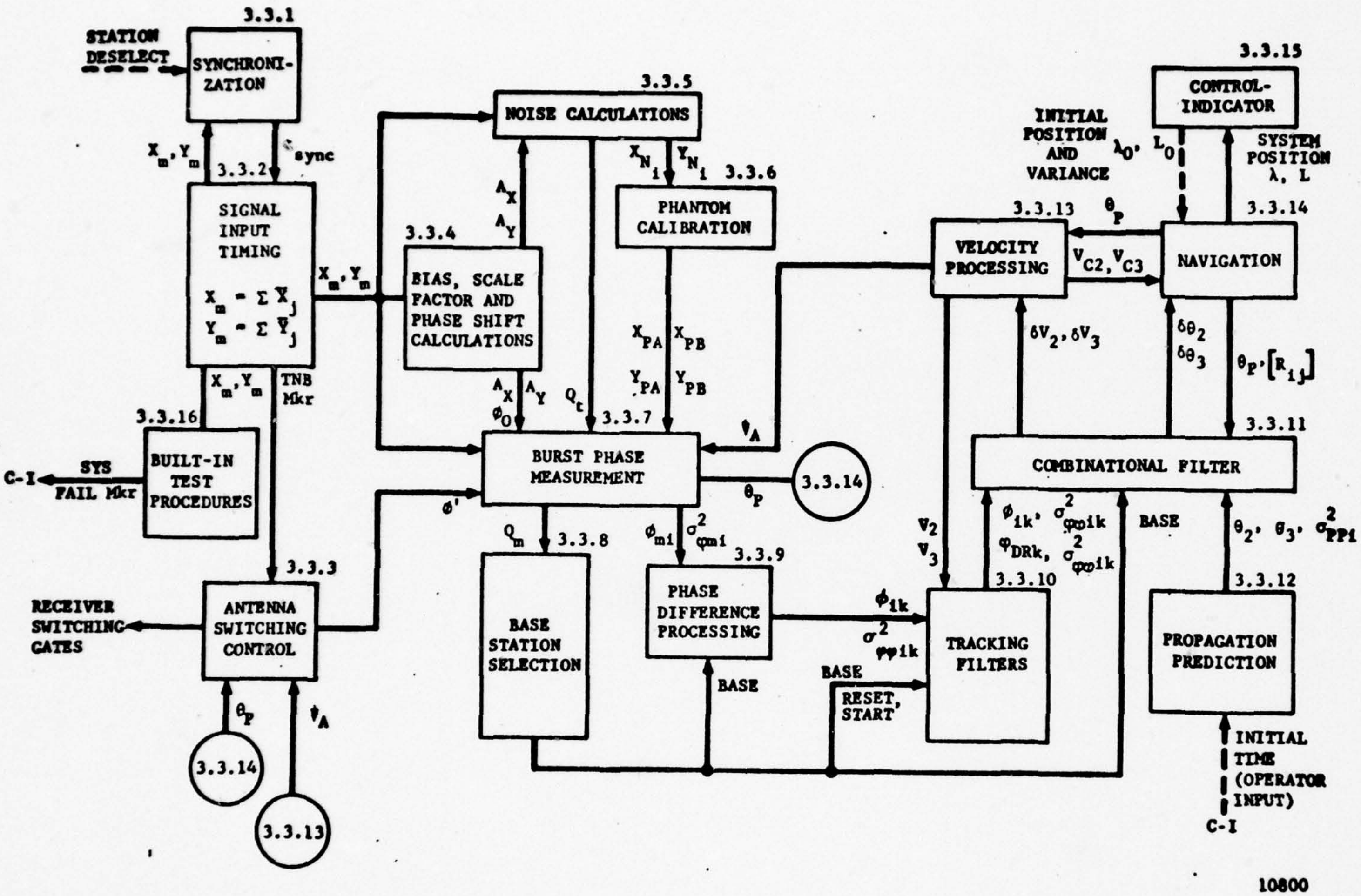


FIGURE 1.1 PRIMARY FUNCTIONAL BLOCK DIAGRAM OF SUBMARINE OMEGA COMPUTER PROGRAM

- 3.3.3 Antenna Switching Control: directs received signals, noise, and test and calibration signal input by gate control in the antenna switching matrices located in the receiver.

- 3.3.4 Bias, Scale Factor and Phase Shift Calibration: determines any bias in the receiver-correlators, system scale factors, and any phase shift introduced by the hardware.

- 3.3.5 Noise Estimation: this measurement will yield an estimate of the credibility of the succeeding signal measurements. An output of 3.3.5 will be input to 3.3.6 Phantom Calibration which in turn will provide the means of eliminating spurious low-order signals which may have been internally generated.

- 3.3.16 Built-In Test: (discussed below).

Most of the above functions will provide inputs to 3.3.7 Burst Phase Measurements, which will calculate phase measurements by combining the sine and cosine inputs, then calibrating and removing all fixed and variable phase shifts. It will also obtain a measure of the credibility of the phase which will eventually aid in determining how much weight is given the measurement in the Combinational Filter.

The Burst Phase Measurement estimates the difference in phase between that received from a station and that of the OMEGA oscillator. However, the Submarine OMEGA Computer Program operates with a hyperbolic processing concept which means that a station-to-station difference is utilized. This concept is necessary to eliminate a variable phase-shift whose value is dependent on antenna depth. Consequently, 3.3.9 Phase Difference Processing satisfies this requirement by differencing the inputs from each station with that of another designated as base. The base station is selected by 3.3.8 Base Station Selection using a criterion dependent upon a relative maximum value of the three frequency signal strength from each station.

These station to base station phase differences are filtered by the Tracking Filters, 3.3.10, whose function is to delay each phase difference until the accumulated credibility estimate indicates that the measurement is usable by the main processor - the Combinational Filter.

In order to synthesize the Tracking Filter estimates into a position estimate, the Combinational Filter needs real world data; specifically, the real world propagation velocity of the signals from each station. This data is provided by 3.3.12 Propagation Prediction, which provides data on earth model phenomena. These phenomena are based on parameters such as: temporal-geographical ionospheric variations, nonspherical earth effects, and magnetic latitude characteristics. The effects of these variables on the velocity of propagation are made available to the Combinational Filter.

Using inputs from the Tracking Filters and Propagation Prediction, the Combinational Filter processes the information and arrives at system velocity and position corrections to be sent to 3.3.13 Velocity Processing and 3.3.14 Navigation, respectively. Velocity Processing may also process velocity inputs from the EM Log Repeater, and heading inputs from the Mark 19 Repeater.

Outputs from many of the above functions are available on the Control-Indicator Panel, whose function is indicated as 3.3.15. The two necessary inputs from the Control-Indicator are initial position and time (shown as dotted lines in Figure 1.1).

Intimately associated with the hardware, though independent of the primary purpose of the OMEGA software, are 3.3.16 and 3.3.17: Built-In Test Procedures and Built-In Test Equipment, respectively. These important functions are also discussed in detail in the section designated by the functional block number.

SECTION 2

APPLICABLE DOCUMENTS

2.1 PROGRAM DEFINITION DOCUMENTS

a) NORT 67-133A, OMEGA Propagation Correction Technique Study Final Report, October 1967, Contract No. N-00953-67-M-5343.

b) NORT 67-164, Proposal for an Airborne OMEGA Navigation Set AN/ARN( ), November 1967.

c) NORT 69-48, NDC-1070 Support Equipment and Program Manual, May 1969.

d) Airborne OMEGA Project Data Manual, Code 22915

e) ELEX-R-122 Specification, Radio Navigation Receiving Set, Omega, AN/BRN-7.

2.2 MISCELLANEOUS DOCUMENTS

The following documents pertain to the application of the OMEGA Computer Program to operational requirements defined by other agencies.

a) NORT 69-93, Mechanization Approach for the P-3C OMEGA Navigation System, Final Report, August 1969, Contract No. N62269-69-C-0393.

b) NORT 71-28, OMEGA Navigational Set, AN/BRN-99(XN-1), April 1971, Contract No. N00019-68-C-0355.

SECTION 3

REQUIREMENTS

3.1 INTRODUCTION

The Northrop AN/BRN-7 OMEGA Navigation Set is a production system designed and developed in accordance with Naval Electronic Systems Command specification ELEX-R-122 for use in submarine navigation. The navigation set includes a Receiver-Computer unit, Control-Indicator, and Interface Box unit. It is designed for use in all types of surface and undersea vehicles, and will operate with either an orthogonal loop, or floater antenna.

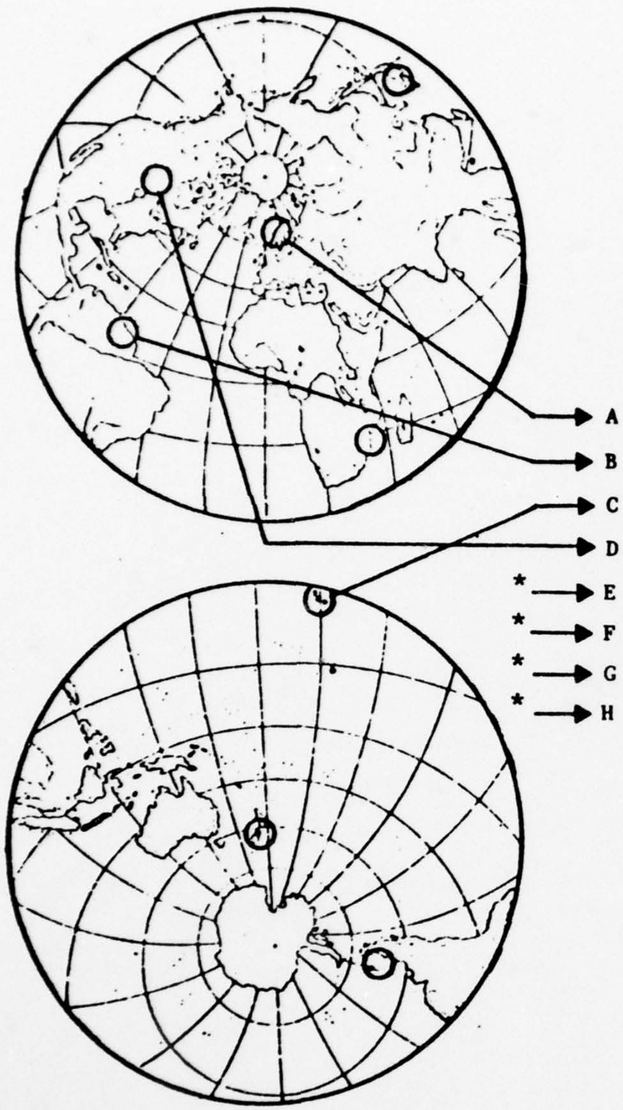
3.1.1 OMEGA Task and System Breakdown

OMEGA is a radio navigation system which uses eight broadcasting transmitters for full world coverage. Figure 3.1-1 shows four of the stations presently in operation as well as the planned locations of the remaining four. The AN/BRN-7 system is designed to operate on from three to eight broadcasting stations. This description will assume that all eight are operating.

Each of the eight stations transmits a sequence of three CW pulses, hereafter referred to as "bursts". The first burst will be on 10.2 kHz, the second on 13.6 kHz and the third on 11-1/3 kHz. The duration of each burst is approximately one second; specifically the total span of a burst varies between 0.9 and 1.2 seconds with a non-transmission time between bursts of 0.2 second. After the third burst the station will not transmit for approximately 6-1/2 seconds. This total OMEGA transmission pattern repeats every 10 seconds.

Figure 3.1-1 shows the specific synchronization relationships between stations. The eight stations are represented as letters A through H on the left of the transmission pattern and pulse length is represented in seconds across the top. The separation line between bursts represents the 0.2 second period of non-transmission. Notice that at any point in time (except during the 0.2 second off-time) there are three bursts being transmitted, one from each of three stations, one on each of the three frequencies. To receive the simultaneous bursts on each of the three frequencies, the Airborne OMEGA system uses not one, but three receivers, each tuned to one of the OMEGA frequencies.

Thus there are eight stations and three frequencies; twenty-four bursts in each 10-second period. How are the frequencies and bursts related? First, each OMEGA transmitting station uses an atomic clock to generate all three frequencies. Each frequency is time-synchronized, which means that for each station and each frequency the representative sinusoid will rise from zero at universal time-zero. This not only synchronizes each transmitter to absolute time but to each other as well.



OMEGA TRANSMISSION SCHEDULE

BURST DURATION (in seconds)

Each shaded area represents a 0.2 second period of non-transmission.

	0.9	1.0	1.1	1.2	1.1	0.9	1.2	1.0
A	L	H	M					
B		L	H	M				
C			L	H	M			
D				L	H	M		
* E					L	H	M	
* F						L	H	M
* G	M						L	H
* H	H	M						L

where L = 10.2 kilohertz
H = 13.6 kilohertz
M = 11.3 kilohertz

*Precise locations to be determined.

10697

FIGURE 3.1-1 OMEGA TRANSMITTER LOCATIONS AND BROADCAST PATTERN

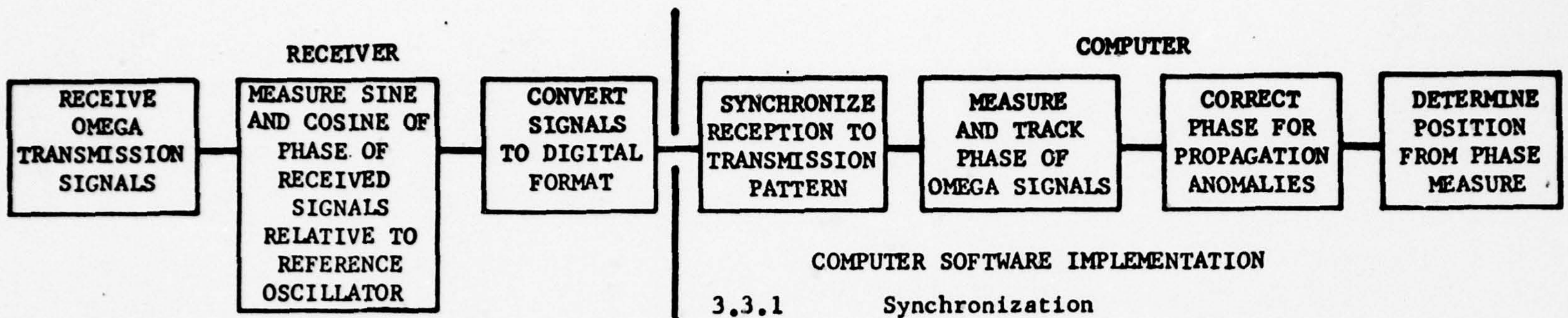
Second, the CW burst pattern, shown in Figure 3.1-1, must be fixed in time. This is done by the logic gates that permit a frequency to reach the antenna and become a transmitted burst. Once the opening gate for any burst from any station is fixed in time then the entire pattern is fixed and is predictable at every moment. The gate from station A, Norway, on 10.2 kHz begins at universal time-zero.

Each receiver uses a reference oscillator to measure the difference in phase between itself and the incoming CW bursts. This oscillator is not as precise as the atomic clock of the transmitting stations, and thus may drift. Also, when the OMEGA receiver is turned on the oscillator zero time is unknown. However, the fact that the receiver oscillator is not time-synchronized to universal time zero is unimportant, for either the measurements from two stations can be differenced, thus subtracting out the arbitrary oscillator zero time, or the error in receiver oscillator zero time can be calculated, and its drift measured and tracked, thereby permitting single station phase measurements. Position fixing by the first method, using two-station, difference measurements, is referred to as hyperbolic navigation; position fixing by the second, which uses the phase measurements from each station, is called circular or rho-rho navigation. The Northrop Submarine OMEGA system uses the hyperbolic navigation concept.

Figure 3.1-2 is a first-level functional flow diagram that shows those independent functions that must be accomplished within an OMEGA Navigation Set. It also indicates which portion of the system accommodates the indicated function. The computer-optimized approach replaces complicated and special purpose hardware design with unique software that maximizes the use of information theoretic techniques.

3.1.1.1 Receiver Description

The OMEGA Navigation Receiver is a single conversion heterodyne design utilizing an RF section and an IF section. The filtering requirements placed upon the RF and IF sections of this receiver are quite demanding. The RF filtering must effectively remove the RF image as well as frequencies in the region of the harmonics of the local oscillator used to convert the output of the RF amplifier down to the IF frequency. As is normally expected in a superheterodyne configuration, the IF will furnish the very narrow band characteristics required of the overall system. In addition to the above basic filtering requirements on the RF and IF filters, certain other constraints must be placed on the circuitry owing to the specific nature of the receiver. The limiters which are utilized here to control the dynamic signal levels present, introduce harmonics by their very nature. Consequently following the limiter is a bandpass filter which removes these harmonics, leaving the fundamental frequency as a sinusoid so that the correlator, using a square reference signal, yields sine and cosine outputs.



HARDWARE IMPLEMENTATION

- Antenna
- Antenna Coupler
- Antenna Switching Matrix
- Receiver Strips
- Correlators
- Digital Outputs

COMPUTER SOFTWARE IMPLEMENTATION

3.3.1	Synchronization
3.3.2	Signal Input Timing & Control
3.3.3	Control Antenna Switching Matrix
3.3.4	Bias, Scale Factor and Phase Shift Calibration
3.3.5	Noise Estimation
3.3.6	Phantom Calibration
3.3.7	Burst Filter (Apply Receiver Phase Shift and Correlator Calibration, and Phantom Correction)
3.3.8	Base Station Selection
3.3.9	Phase Difference Processing
3.3.10	Adaptive Tracking Filter
3.3.11	Combinational Kalman Filter and 3-Frequency Lane Resolution
3.3.12	Propagation Correction
3.3.13	Velocity and Heading Processing
3.3.14	Navigation
3.3.15	Control-Indicator Routines
3.3.16	Built-in Test Procedures
3.3.17	Built-in Test Equipment

10698A

FIGURE 3.1-2 FIRST LEVEL TASK AND SYSTEM IMPLEMENTATION FOR OMEGA NAVIGATION

3.1.1.2 Receiver Function

A burst, picked up by the antenna, is RF amplified, then beat down in the first mixer of the IF. After additional amplification and bandpass filtering, each IF burst is fed to two mixers (choppers), and the output is composed of two dc signals; one representing the sine of the burst phase and the other the cosine.

The sine and cosine phase representations are slightly inaccurate due to a phase shift introduced by the hardware. It will be removed in the first stage of the software subroutines.

These dc phase representations with the phase shift enter the phase-to-digital converter where they are sliced up into integrated periods of 5 milliseconds and transmitted to the Burst Filter subroutine of the computer after the OMEGA receiver system has been synchronized to the incoming pattern.

3.1.1.3 Computer Description

The more important characteristics of the Submarine OMEGA computer are listed in Table 3.1-1. A further breakdown and description of the computer software follows.

3.1.1.4 Computer Software Functions

3.1.1.4.1 Synchronization: Rapid automatic synchronization to the transmitted signals is essential to effective utilization of OMEGA in submarines. Since a high-speed general-purpose computer is part of the Submarine OMEGA Navigation Set, synchronization techniques based on the numerical application of information theory can be used.

Synchronization incorporates the statistical probability of the presence of a phase-stable signal, correlated against the known OMEGA format. The fact that precise phase measurements are not required is important in that the effect of oscillator drift during warm-up does not affect the synchronization process.

Three correlation techniques were investigated to determine the method that produces the fastest synchronization under high noise conditions. Differential Burst Correlation was selected. Since no other operations are required of the computer during synchronization, except navigation and display, the full capabilities of the computer can be used to achieve this end. Differential Burst Correlation does utilize a major portion of real computational time. However, after synchronization is achieved the computer time is completely released for other functions and synchronization is maintained by the reference oscillator.

TABLE 3.1-1 CHARACTERISTICS OF THE BRN-7 RECEIVER-COMPUTER

Type	A militarized, general-purpose, digital computer designed for aerospace applications, with conductive cooling, parallel magnetic core memory, and serial, single-address arithmetic.
Clock Frequency	4.5 MHz
Memory	Magnetic cores; non-volatile, random access, DRO
Size	8,192 words (expandable to 16,384 within same case size)
Word Length	16 bits
Cycle Time	2.0 microseconds
Access Time	1.0 microsecond
Arithmetic	Serial, 2 bits at a time
Number System	Binary, fixed-point fractional; with negative numbers in two's complement form
Data Formats	16 bits (single precision) or 32 bits (double precision)
Add	2 microseconds - interregister (16 bits) 6 microseconds - 16-bit memory register
Multiply	6 microseconds - interregister (16 bits) 8 microseconds - 16-bit memory register
Instructions	
Total	73
Instruction Formats	16 bits (short) or 32 bits (long)
Addressing	Single memory address per instruction
Features	1) 16 16-bit general registers 2) Indexing with no increase in execution time 3) Relative addressing 4) Roll Table (pushdown stack) operation 5) Indirect addressing 6) Immediate addressing
Interrupts	Two types: 1) At the memory cycle level (Direct memory access) 2) Program interrupt
Circuits	Multi-functional TTL micro-integrated circuits (MIC)

3.1.1.4.2 Signal Input Timing and Control: The 5 millisecond signal inputs from the receiver are sine and cosine correlator outputs which are, at different times, representations of incoming OMEGA signals, representations of test and calibration inputs and sometimes just noise. Signal Input Timing and Control is the managing system which notifies each input related algorithm when the pertinent signal has arrived.

3.1.1.4.3 Antenna Switching Control: When using the orthogonal loop antenna it is advantageous to select one of either loops to enhance the signal-to-noise ratio. The antenna selection subroutine in the computer calculates the optimum antenna lobe configuration using the submarine heading and position, and the station location as inputs. The antenna switching matrix in the receiver uses these control inputs to switch in either Loop A or B. When the Floater antenna is used all signals are input through Loop A.

3.1.1.4.4 Bias, Scale Factor, and Phase Shift Calibration: Separating each incoming transmission (burst) is a 0.2-second period of non-transmission. During every other non-transmission period a calibrated signal is injected into the front end of the receiver. With this signal the computer software will not only determine that the system is operating properly, it will also measure and compensate for bias in the dual slope integrator, and determine component value drifts which affect the values of the correlator ratio detector (scale factor calculations). The phase shifts due to the use of alternative hardware components are also summed for eventual adjustment to the phase measurement.

3.1.1.4.5 Noise Estimation: Noise estimation is used to establish the credibility of each phase measurement. The Submarine OMEGA Computer Program uses a Kalman filter which requires that the phase difference measurements which are accumulated and averaged in the tracking filters, pass a credibility criterion before transmittal to the Combinational (Kalman) Filter. The smaller the existing signal-to-noise ratio the longer it takes the credibility value in the tracking filter to pass the criterion for transmittal to the Combinational Filter.

3.1.1.4.6 Phantom Calibration: It is possible that the hardware circuitry may sometimes generate interfering signals of its own. They are usually of low amplitude and constant and are referred to as phantoms. The equations represented by this function insure against their interference with the phase measuring process by detecting and removing them.

3.1.1.4.7 Burst Filter: The function of the Burst Filter is to collect the sine and cosine receiver outputs and calculate the first crude phase measurement as well as an estimate of its credibility based upon the signal-to-noise ratio (from Noise Estimation). It is the combination of the Burst Filter processing and the correlators in the receiver which constitute that referred to as the correlator ratio detector. The resultant phase is corrected for phase errors introduced by the hardware. The measurements, phase, and estimate of validity are transferred to the phase differencing equations before submittal to the Tracking Filters.

3.1.1.4.8 Base Station Selection: The application of station-to-station phase differencing necessitates the selection of one available station as the base station. The base will be that available station with the greatest three-frequency signal amplitude.

3.1.1.4.9 Phase Difference Processing: The phase differences, station to base (and base to base), are handled by the Phase Difference Processor and transmitted to the Tracking Filters. The base-to-base differences, taken 10 seconds apart, are used for drift rate calculations.

3.1.1.4.10 Tracking Filters: Since there are eight possible transmitting stations and three frequencies for each station, there are 24 Tracking Filters. Each Tracking Filter receives an input from the phase differencing equations once every 10 seconds. After differencing, the input to the Tracking Filter consists of a measure of phase difference and a computed variance of this measurement. This measured phase difference is then compared (or weighted in a statistical sense) with an estimated value of phase difference which the Tracking Filter computes based upon previous measurements. From this comparison a new estimate of phase difference is computed.

In order to compare or statistically average successive phase difference measurements spaced 10 seconds apart in time it is necessary to remove the effect of the change in phase due to submarine motion. This compensation is referred to as rate aiding. Velocity information is obtained from either the E.M. Log Repeater (external source), or the OMEGA software (internal source). Only one velocity source at a time is used. The priority of use is in the order listed. The velocity inputs to the Tracking Filter consist of the north and east components of velocity averaged over the previous time interval. The Tracking Filter then computes the component of velocity along the direction from the submarine to the transmitting station and then from the submarine to the base station, and from this calculates the phase difference rate. This rate is then used to update the Tracking Filter phase difference estimate over the 10-second interval since the last measurement.

In addition to estimating phase difference, the Tracking Filter also estimates phase difference rate errors. This is the error in phase difference rate as computed from the velocity sources. The estimated phase difference rate error is used to correct the computed phase difference rate in the time update of the phase difference estimate.

3.1.1.4.11 Combinational (Kalman) Filter: The outputs of the Tracking Filters are well-filtered values of phase difference along with the estimates of phase difference variance and phase difference rate variance. It is within the Combinational Filter operations that the outputs of the Tracking Filters are statistically, optimally combined, arriving at "best" error estimates of system position, velocity, and oscillator drift. The error estimates of system position are transmitted to the navigation equations as rotational corrections about the axes of the reference triad while the velocity error estimates are transmitted to Velocity and Heading Processing as corrections along the axes. The error estimate in oscillator drift measures the phase and frequency differences between the local oscillator in the receiver and the transmitted OMEGA signals.

The Combinational Filter is also used for lane determination. Lane determination (laning) is accomplished by use of a multiple state vector technique. The wavelength of each frequency determines a lane within which the receiver position can be determined. The widths of these phase difference lanes are 6, 7.2 and 8 miles, corresponding to the frequencies of 13.6, 11-1/3, and 10.2 kHz, respectively. At intervals of 72 miles these lanes repeat, thus defining a larger three-frequency lane width. Resolving the known phase (position) from each frequency into the larger lane is referred to as resolving the lane ambiguity. A three-channel OMEGA receiving set operating in the hyperbolic mode has the capability of resolving lane ambiguities up to 72 nautical miles.

3.1.1.4.12 Propagation Prediction: Operation of the OMEGA Navigation System is based on the measurement of the phase of several transmitters operating in the 10-14 kHz electromagnetic spectrum. It has been established that the eight proposed OMEGA transmitters will cover the earth with signal levels adequate to permit that phase measurement. Furthermore, it is generally accepted that signals in this spectrum behave as though they propagated through a waveguide made up of two concentric spheres -- one sphere is the earth, the other is the ionosphere.

Under ideal conditions a simple phase measurement would suffice to precisely determine the distance from a transmitting station. However, the walls of the waveguide are not perfect and are affected by many factors, including the effect of the sun on the ionosphere, the direction of the earth's magnetic field, ground conductivity, oblateness of the earth, and others. These anomalies in the waveguide walls cause changes in the phase velocity, which introduces an error in the distance determination.

The phase velocity of such waves in an ideal waveguide with this geometry depends on the width of the waveguide (the height of the ionosphere) and on the electrical conductivity of the surfaces. The electric conductivity of the earth's surface is important, as well as that of the ionosphere. In the case of the ionosphere, the problem is complicated theoretically because a well defined wall does not exist; rather, the electron density (and collision frequency) vary with altitude in a manner which is approximately exponential. The effect of the earth's magnetic field on the phase velocity, which must also be considered, has been analyzed theoretically and the assymetry between propagation from east to west and from west to east determined.

These factors, along with compensation for the oblateness of the earth, are incorporated into a computer program that provides incremental real-time corrections along the propagation path.

3.1.1.4.13 Velocity and Heading Processing: The velocity and heading processor smooths inputs from the ship's heading and speed references as well as velocity corrections from the combinational filter. Corrected velocities are sent to the navigation equations.

3.1.1.4.14 Navigation: Position corrections from the combinational filter are in the form of rotational corrections to be applied to the matrix representing the navigational axes (reference triad). System latitude and longitude can be extracted from this matrix.

3.1.1.4.15 Control-Indicator Processing: The control-indicator routines will access system position and velocity information as well as range, bearing and estimated time enroute to both fixed destinations and rendezvous with another vehicle. See Section 3.3.15 for a complete description.

3.1.1.4.16 Built-In-Test (Equipment): These are computer program requirements imposed by the hardware and are described in Sections 3.3.16 and 3.3.17.

3.2 FUNCTIONAL DESCRIPTION

3.2.1 Introduction

This subsection describes the functional relationships and imposed requirements on the computer program with interfacing equipments (Figure 3.2-1) which include the computer, the receiver, antenna and coupler, control-indicator, and ship's heading and speed references.

The input/output requirements imposed on the computer program by the hardware fall under two categories: those related to solving the OMEGA problem, and Built-in-Test requirements which insure the operability of the hardware involved.

3.2.1.1 General System Operation

Primary power is supplied from two circuit breakers. When the breakers are closed, single phase, 400~115v power is available at the receiver-computer, control and indicator panel, dc power supply, and an auxiliary plug which can be used for the maintenance panel. The dc power supply must be turned on and adjusted to +28 vdc. The control and display panel must then be turned to the STANDBY mode to apply 28 vdc power to the oscillator oven and sufficient time allowed for the oven to thermally stabilize before going to the OPERATE mode. In the OPERATE mode, power is applied to the whole OMEGA system and the computer automatically starts up.

The computer used in the system is programmed to perform self test, on-line monitoring self test, and mathematical computations necessary to obtain accurate navigational information. Once the system is energized, the computer will automatically initiate self test. Upon completing self test, the computer will then initiate on-line monitoring test. When one cycle of this test is completed, specific indicators on the control-indicator will light to inform the operator the OMEGA Navigation Set is ready for operation whenever present position and time are inserted into the computer circuitry. Once inserted, the OMEGA Navigation Set is ready to receive and process the transmitted OMEGA signals

The OMEGA signals transmitted by the VLF OMEGA stations are received through the loop or floater antenna on the submarine and supplied to an antenna coupler. The antenna coupler filters and amplifies the OMEGA signals. The antenna switching matrix circuit sums and phase shifts the coupler output signals and then supplies this signal to the receiver circuit (receiver strips) in the receiver-computer. Each receiver strip is a single conversion superheterodyne receiver which uses RF and IF circuits. Each receiver strip amplifies and filters the signal and then supplies this signal to the correlator and digital converter circuit. The correlator and digital converter circuit obtains sine and cosine phase information from the receiver strip outputs and converts this information into digital form which will

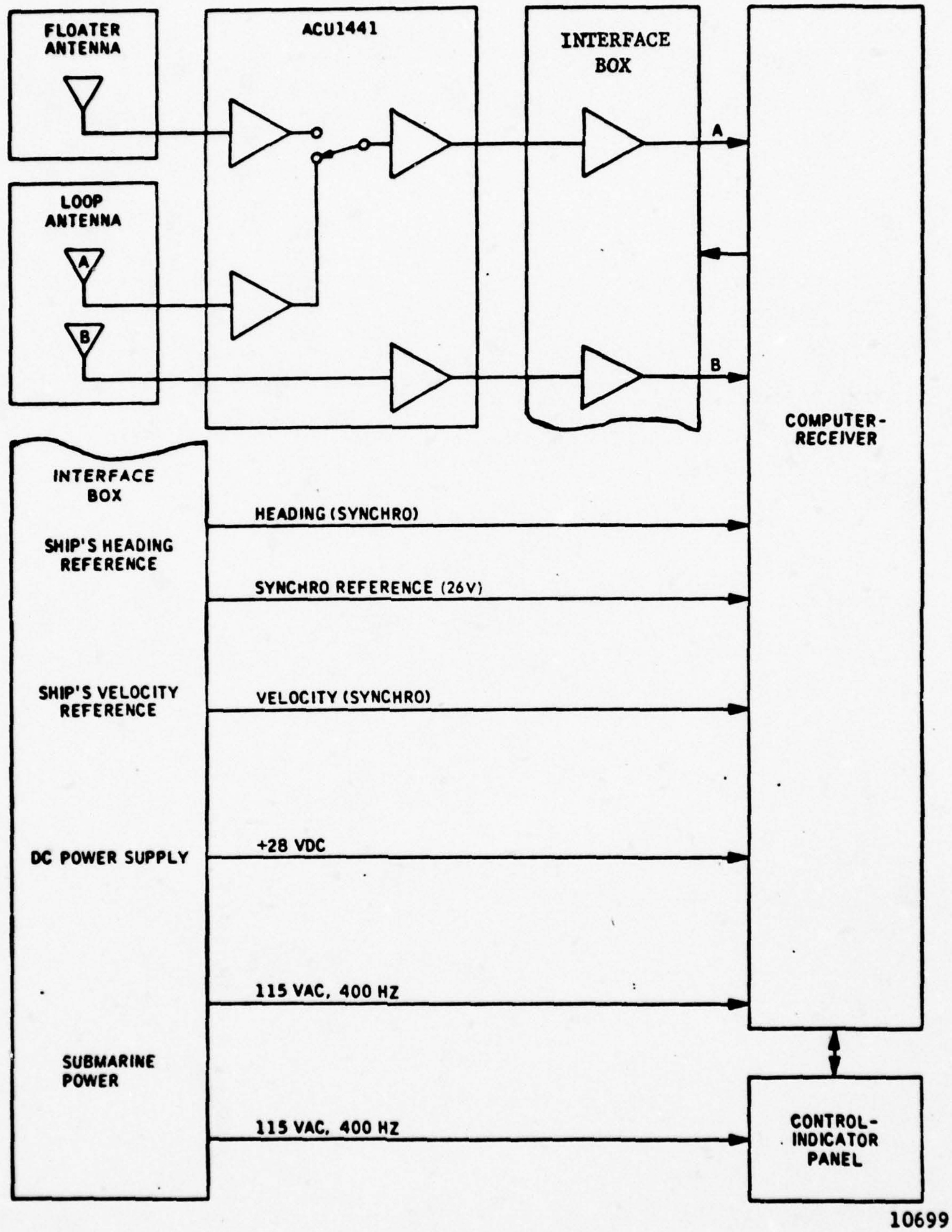


FIGURE 3.2-1 SUBMARINE OMEGA NAVIGATION SET BLOCK DIAGRAM

be compatible with the computer circuit. The sine and cosine information in digital form is supplied to receiver input/output circuit. The receiver input/output circuit counts and stores this information until instructed by the computer to transfer this information for further processing. When instructed by the computer, the software system will begin the synchronization process to align the receiver input/output information with a known OMEGA transmission pattern. Once synchronization is obtained, the computer software system will continue to filter the signals through tracking filters and combinational filters until accurate positional information is obtained.

In order to obtain accurate positional information, the OMEGA Navigation Set must rely on velocity and heading information from sources external to the system or updated information inserted manually by the operator at the Control-Indicator panel. The OMEGA Navigation Set receives the necessary signals from the E.M. Log Repeater gear train and the Mark 19 Repeater gear train respectively. Signals from these external sources are inserted into the computer software system for phase rate aiding and directional antenna selection or for dead reckoning navigation when OMEGA signals are not available. Once positional information is determined and acceptable by the software system, the positional information is shifted into the logic control circuit in the Control-Indicator panel. The logic control circuit conditions the input information and supplies this information into a shift register. The output from the shift register is then supplied to a decoder circuit. The decoder circuit decodes this digital information for display on the front panel to inform the operator the present status of the cruise. The operator can request specific information to be displayed by manipulating the appropriate controls on the Control-Indicator panel.

3.2.1.2 Built-In-Test

The Built-In-Test (BIT) is included in the design in order to satisfy two criteria; first, to provide a functional status check of the system in its operational environment and second, to provide diagnostic capability for dockside and shop maintenance. The BIT will provide the following capability:

- With the Receiver-Computer installed in the submarine --- fault isolation to a functional area in 85% of the cases of Receiver-Computer hardware failures.
- Pre-cruise and post-cruise functional test capability.

The BIT will be implemented by using the computer as the primary test executor. The computer will contain, in permanently stored memory, the necessary program routines to execute the tests described in this section.

In the operational environment, test routine entry will be under program control and in the maintenance environment, test routine entry will be under operator control.

Tests to be implemented are primarily of the end-to-end type, i.e., a stimulus is inserted at the front end of the section under test and response is monitored at the final stage. This method yields GO/NO-GO results and thus enables fault isolation to specific physical assemblies.

3.2.1.3 Built-In-Test-Equipment

The Malfunction Indicator located on the Control-Indicator will signify a system malfunction. This includes inability to detect and/or process OMEGA signals as well as any detectable hardware malfunction. Indicator remains active only during time fault or malfunction is current.

The Receiver-Computer has a Malfunction Indicator which, once it is set by the Built-In-Test, will remain set until reset by the maintenance operator. In addition, the Receiver-Computer will have a separate indicator which will light when the power supply fails, provided that system power is on.

The Interface Box does not have a BITE indicator; the operator, using the diagnostic program loaded by the Programmer Controller, may fault isolate the system including the Interface Box.

3.2.2 Functional Description and Requirements of OMEGA Hardware

The Antenna, Coupler and Interface Box amplifiers provide the means for reception and initial amplification of the OMEGA broadcast signals. The OMEGA receiver-computer processes these signals and computes navigational data. The Control-Indicator provides the means for operator control and system display. The rate-aiding hardware, ship's heading and speed reference provide signal inputs necessary for dead reckoning and are discussed here only as functional inputs to the system. The Programmer Controller is used in the case of equipment malfunction.

The OMEGA Receiver-Computer unit can be considered as being composed of the following functional modules:

<u>Receiver</u>

a) Antenna Switching Matrices

b) Receiver Strips

c) Correlator and Digital Converters

d) Precision Frequency Generator

e) Receiver-Computer Interface

Computer

a) Memory

b) Arithmetic and Control

c) Input/Output

d) Power Supply

There are requirements for Built-In-Test routines for the above modules, as well as Built-In-Test indicators, both of which are controlled by the computer program. These indicators and requirements will be defined in this section and further characterized in those that follow. In the description of these modules, discussion of the Built-In-Test requirements will be prefixed with the term BIT.

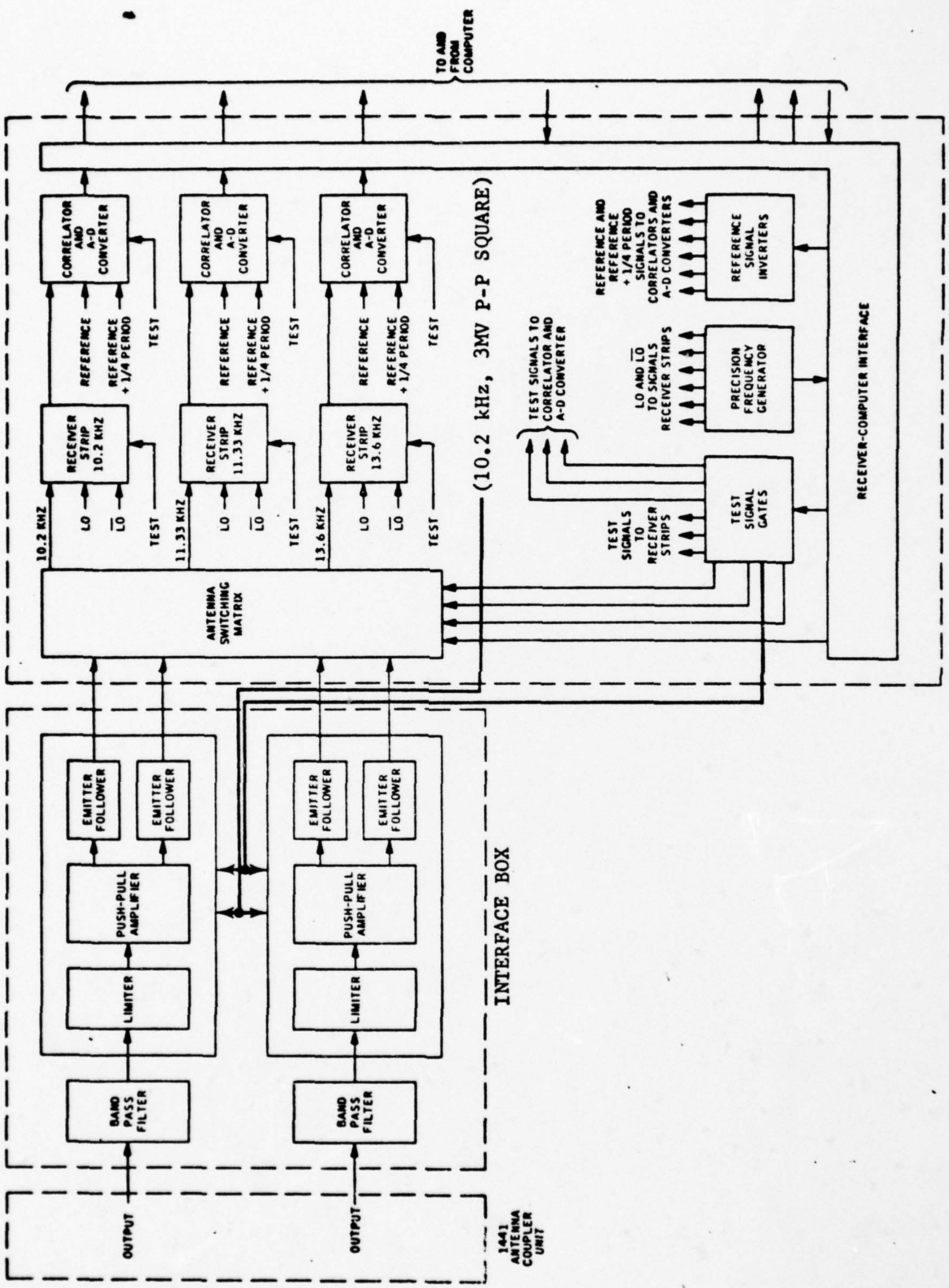
3.2.2.1 Antennas

The OMEGA navigation set uses either the single loop floater or the orthogonal loop antennas which are capable of receiving VLF signals on frequencies of 10.2, 13.6, and 11-1/3 kHz. Both antennas use the same antenna-coupler with loop A and loop B inputs; however, the floater is connected to the A input only. The operating modes of the antennas are discussed under paragraph 3.2.2.3, Antenna Switching Matrices.

Controls: A switch on the CU-1441/BRR Multicoupler must be actuated to select the floater antenna or the orthogonal loop antenna. Also, a switch on the C/I panel must be actuated to inform the computer program which in turn will cause the appropriate antenna signals to be processed through the antenna switching matrix.

3.2.2.2 Orthogonal Loop Antenna Coupler (see Figure 3.2-2)

The amplifiers within the Interface Box provide a means of conditioning the OMEGA signals received from the antenna via the ship's CU-1441/BRR Antenna Coupler Unit. The circuitry consists of dc filter and amplifier circuits. The output from the first stage amplifier is supplied to a push-pull stage where the signal is further amplified and its output supplied to emitter followers. The emitter followers reduce the driving point impedance to a value below that of the transmission line which connects the signals to the antenna switching matrix.



10700

FIGURE 3.2-2 ORTHOGONAL LOOP ANTENNA AMPLIFIER AND OMEGA RECEIVER BLOCK DIAGRAM

3.2.2.3 Antenna Switching Matrices

The antenna switching matrices provide a means of selecting or summing the incoming OMEGA signals in a way to optimize the signal-to-noise ratio for the antenna mode selected and with respect to each receiver channel. It also enables test and calibration signals to be injected into the system.

There are three antenna switching matrices, one for each OMEGA frequency. The component arrangement of one such matrix is shown in Figure 3.2-3. The set of inputs to the matrices consist of signals from loop antenna A and B, loop A-90°, and the negative of B. Provisions are also made for a test signal and a quadrature test signal. The one or more signals from this basic set which will be gated to the system depends upon the requirements of the operational mode and the antenna in use.

These requirements are as follows:

Pseudo Omni-Directional Antenna Mode. This mode is required during the synchronization process. Prior to synchronization the software program cannot yet associate incoming signals with specific stations. Consequently, with the orthogonal loop antenna, a method of combining the signal inputs from both loops simultaneously is required. This is accomplished by the computer program which commands a combination of loop B and loop A - 90° inputs to the switching matrices via the appropriate gates. Using the B and A-90 combination, the phase of each incoming signal will be shifted by an amount proportional to the respective direction of the transmitting station to the orientation of the antenna. However, the software method used for synchronization is related to phase coherency and is independent of phase value.

Since the floater antenna has a single loop, there is no requirement for antenna switching should it be used during synchronization.

Normal Antenna Mode. This mode is used at all times other than at synchronization and at injection of test and calibration signals. With the orthogonal loop antenna the computer program determines and selects that loop which receives the strongest signal by closing the appropriate gates in each switching matrix. Also, since dipolar signals are indistinguishable in the receiver, the computer program is required to take the inverse of those phase measurements known to have arrived at the inverse lobe of the selected loop. Again, for the floater antenna the normal antenna mode is loop A only. However, the computer program is still required to take the inverse when necessary.

Test and Calibration Mode. In order to test the operational capability of the system a signal and its quadrature, both under computer program control, are injected into the system at the switching matrices. All other antenna inputs are gated out. The requirements for test are discussed under 3.3.16 and 3.3.17, and for calibration under 3.3.4.

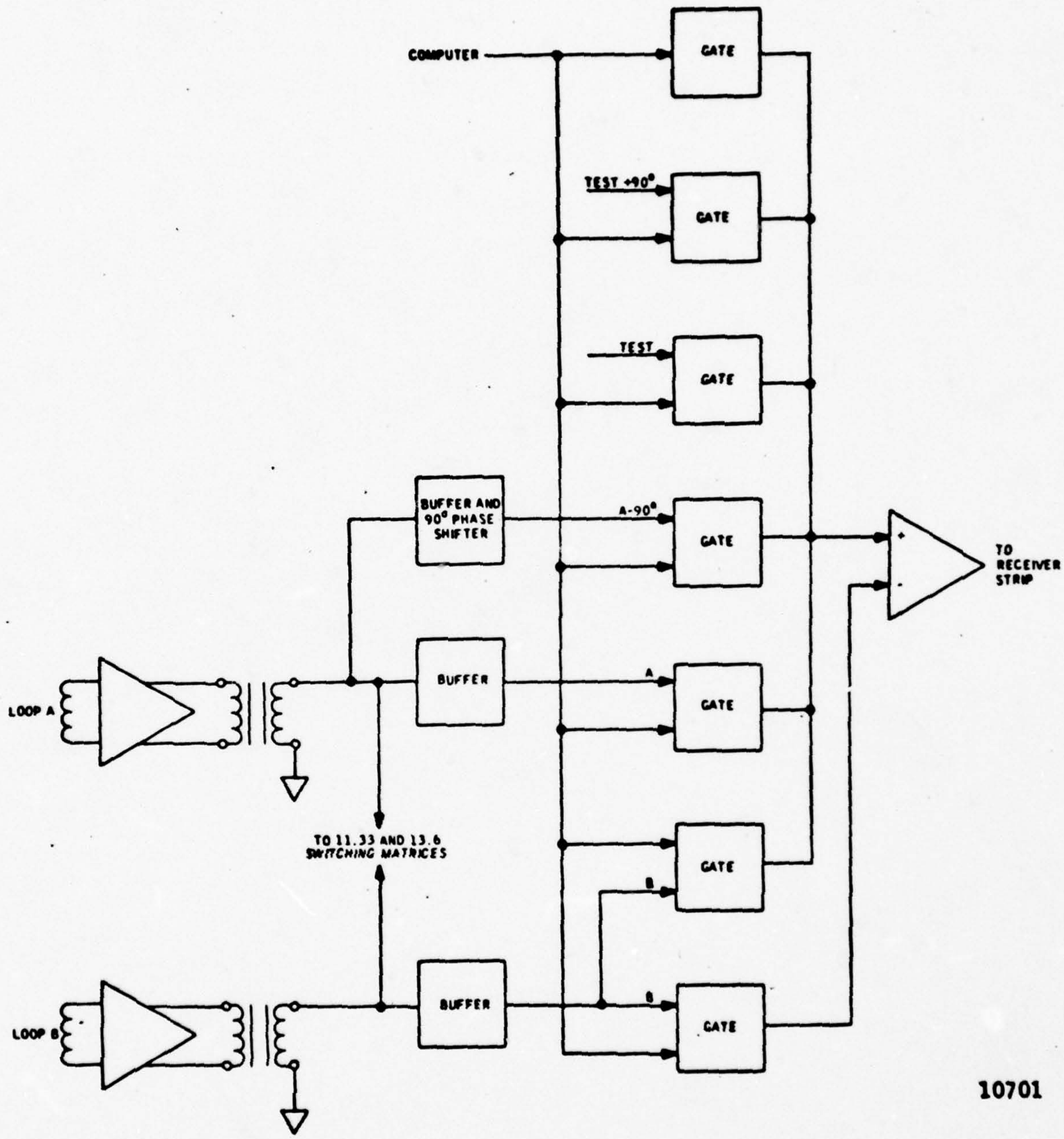


FIGURE 3.2-3 ANTENNA SWITCHING MATRIX CIRCUIT SIMPLIFIED BLOCK DIAGRAM

3.2.2.4 Receiver Strip (See Figure 3.2-4)

Three receiver strips are provided in the receiver-computer. One receiver strip is provided for each OMEGA frequency (10.2, 11.3, and 13.6 kHz). All three receiver strips function similarly except that the rf amplifiers operate at different frequencies. This is accomplished by tuning the band-pass filters to the appropriate frequency. Table 3.2-1 summarizes the differences among the three rf amplifiers.

TABLE 3.2-1 SUMMARY OF RF AMPLIFIER CONFIGURATION

Band Center Frequency	Local Oscillator Frequency	Notch/IF Image Frequency	Inter-mediate Frequency	Q of Bandpass Filters
10.2 kHZ	11.3 kHz	12.46 kHz	1.13 kHz	15
11.3 kHz	10.2 kHz	9.073 kHz	1.13 kHz	15
13.6 kHz	14.73 kHz	15.86 kHz	1.13 kHz	15

In the OMEGA Navigation System, the important intelligence carried by the OMEGA signal transmission is its phase. The receiver strip must maintain phase stability over a wide dynamic range of signal level in the presence of random and impulse noise. In addition to these noises, each receiver strip must provide sufficient skirt rejection to assure that strong man-made interference, near or far from the navigation frequencies, will not interfere with the operation of the receiver system.

Each receiver strip is a superheterodyne receiver consisting of RF and IF circuits which is capable of processing the appropriate OMEGA signal to provide gain, narrowband filtering primarily for rejecting off-channel interfering carriers, and dynamic limiting. Linear filtering is obtained by the use of active filter techniques. This enables accurate system function implementation by circuitry that can tolerate the wide dynamic ranges required while maintaining phase stability. The filtering in the RF circuit notches out the IF image by 75 db and provides sufficiently steep skirts to assure that signals far from the band center do not enter the IF amplifiers. The filtering in the IF circuit provides the narrowband (80 db at 200 Hz) characteristics required of the overall system. The gain distribution and dynamic limiting characteristics of the receiver strip have been optimized to meet the dynamic range of signals. As the input signal varies over a range of 120 db, the signal levels within the receiver will adjust themselves accordingly. Limiters have been placed with the signal flow path in order to control the dynamic level of the signals present within the linear circuitry. It is desirable that the limiters appear as linear amplifiers at low signal levels and a device showing controlled saturation as the signal levels approach and exceed the limiting level.

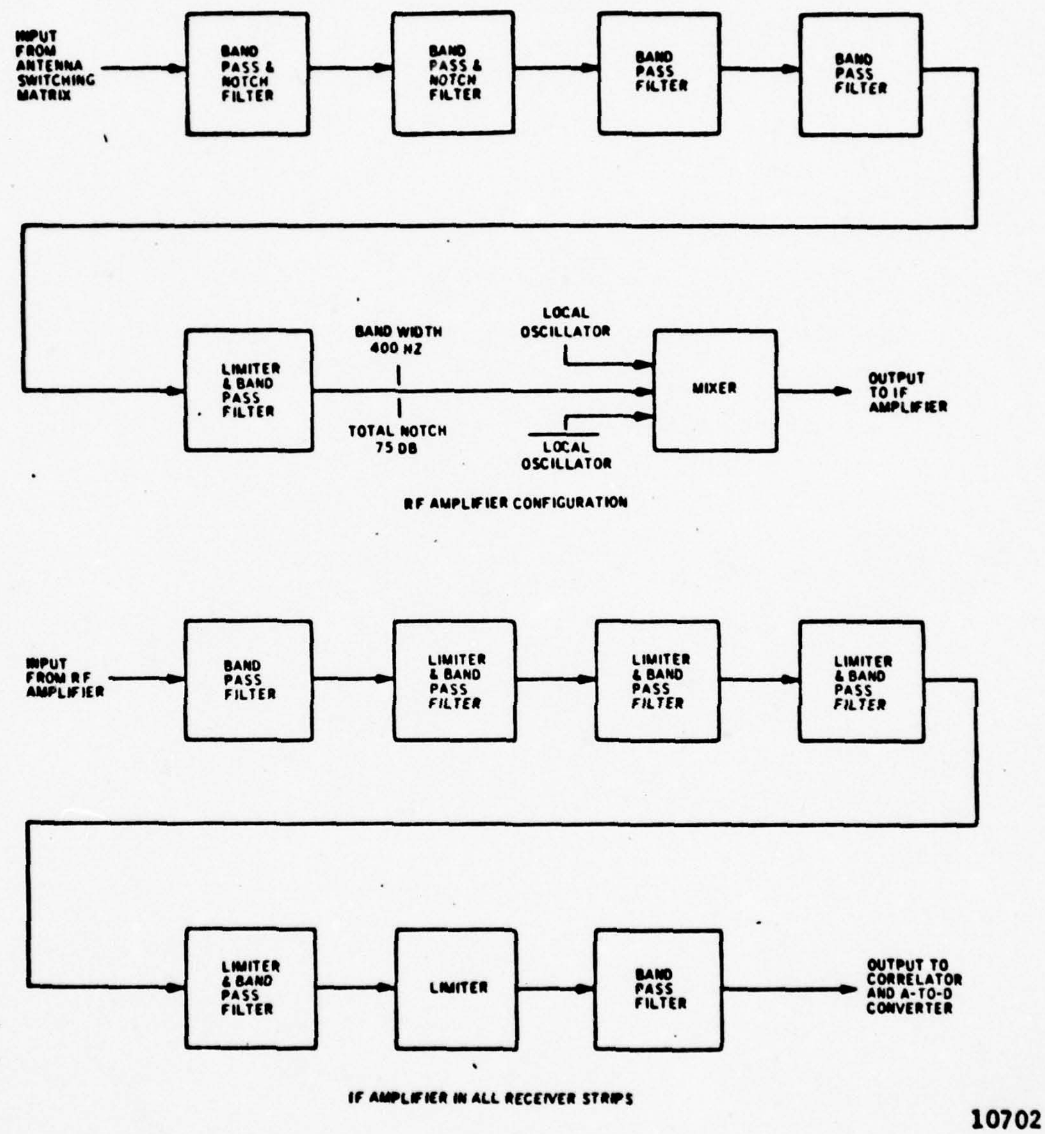


FIGURE 3.2-4 RECEIVER STRIP SIMPLIFIED BLOCK DIAGRAM

The IF output signals from the receiver strips are supplied to the mixer circuit in the correlator and digital converter circuits.

BIT. RF Test. The receiver strips are tested by means of the RF Test. Under computer program control, test and test quadrature signals are derived directly from the precision frequency generator and are coupled directly into the input of each switching matrix in a manner identical to the normal (operational) signals. The signals are passed through the receiver strips, the correlators and digital converters, and the receiver-computer interface, then read and compared by the computer program to insure a 90° (or 25 cec) difference.

This test, in conjunction with the Phase Angle/Digital Converter test, will verify receiver strip operation.

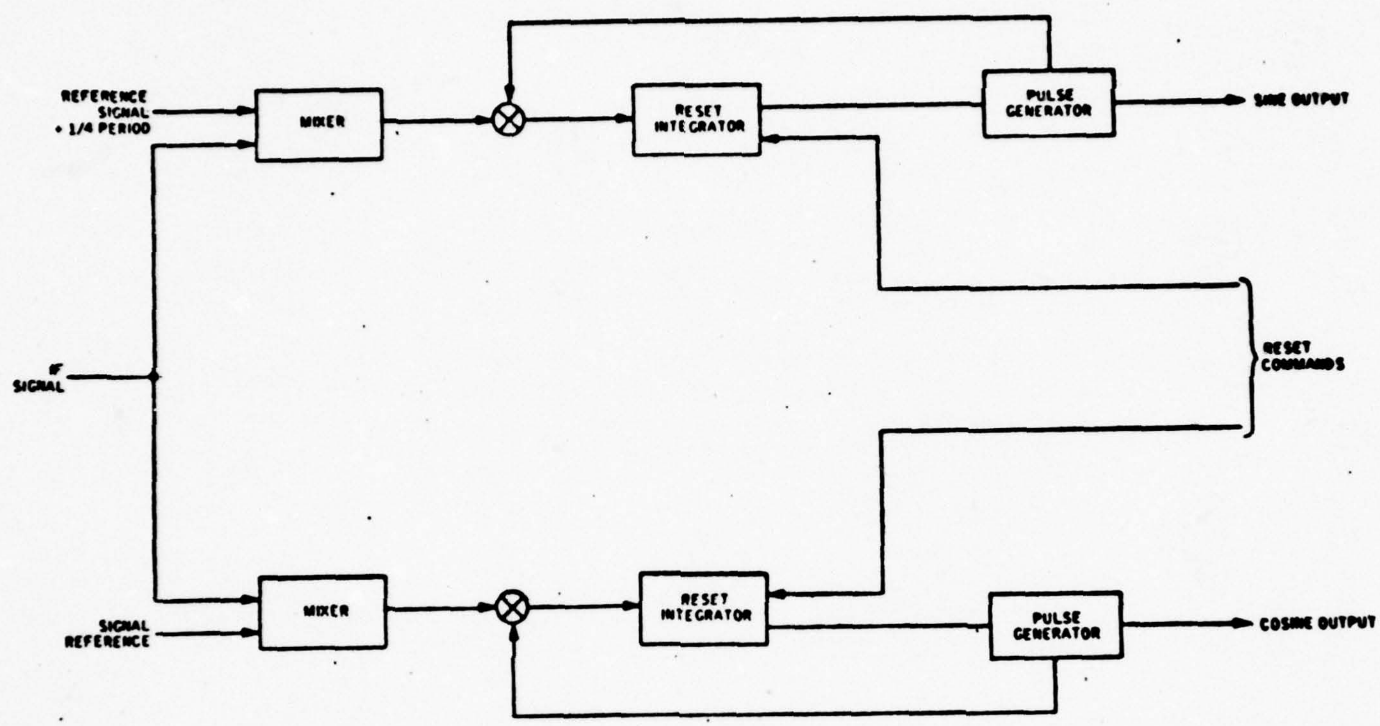
3.2.2.5 Correlator and Digital Converter

The correlator and digital converter circuit (Figure 3.2-5) initiates the signal measurement process which is completed in the computer section.

By definition, the multiplication and subsequent time integration of an input waveform by a known reference waveform is a correlator. Here the input waveform is the IF signal which is input to separate mixers; one multiplies the IF signal by a square wave sinusoid reference signal, the other multiplies the IF signal by the sinusoid shifted by one-quarter period (cosine). The output of each mixer is the input to a dual-slope integrator whose output is digital and is collected in the up-down count accumulator buffer (circulating register), then input to the phase counter memory registers in the computer. There are seven phase counters; two for each OMEGA frequency and one for testing purposes.

BIT. Verification of correlator and converter operability is accomplished by means of the Phase Angle/Digital Converter test. Test signals derived by plus 5-volt power source are coupled directly into the mixer circuit of the correlators. These signals will cause a specific value to appear at the output of each of the six converters. The computer program will read and compare these values with stored values to determine a GO/NO-GO condition.

The Phase Counter I/O test is designed to check the communication link between the receiver and the computer. The test exercises all the functions of the up-down count accumulator buffer and the Direct Memory Access (DMA) registers or phase counters in the computer. This test, in conjunction with the Phase Angle/Digital Converter test above, will isolate malfunctions either to mixer and dual slope integrators, or to the digital conversion circuitry in the receiver-computer interface module.



10703

FIGURE 3.2-5 CORRELATOR AND DIGITAL CONVERTER CIRCUIT SIMPLIFIED BLOCK DIAGRAM

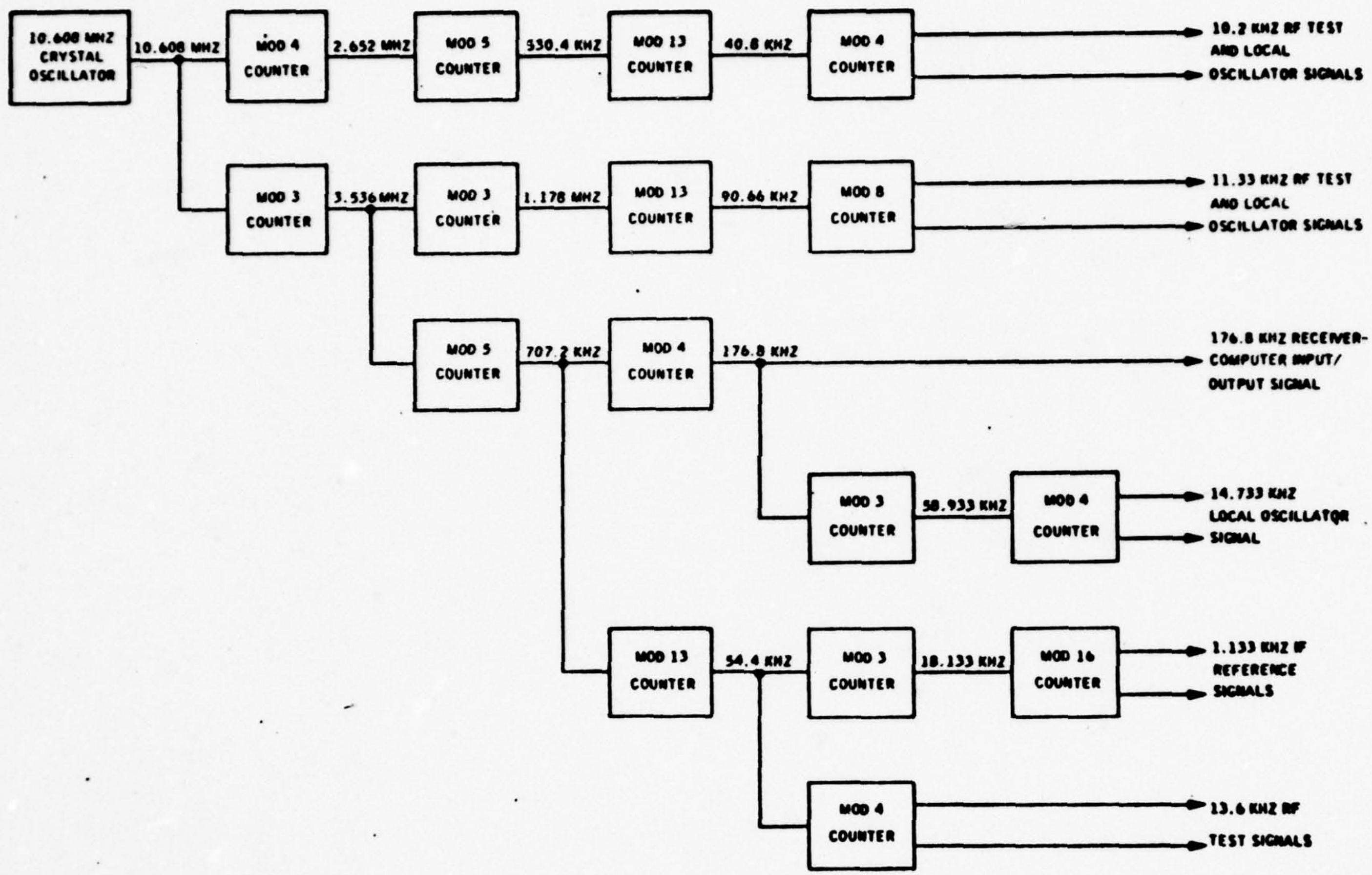
3.2.2.6 Precision Frequency Generator (See Figure 3.2-6)

The precision frequency generator circuit provides a means of generating precision frequency signals required for operation of the OMEGA Navigation Set. The precision frequency generator circuit consists of a precision 10.608 mHz crystal oscillator and MOD counters. The counters are used to divide the crystal frequency to provide 13.6 kHz RF test signal, 1.133 kHz IF reference signal, 14.733 kHz local oscillator signal, 176.8 kHz receiver-computer input/output clock signal, 11.33 kHz RF test and local oscillator signal, and 10.2 kHz RF test and local oscillator signal. Figure 3.2-6 illustrates how the output from the crystal oscillator is divided to provide the different frequency signals required for operation of the OMEGA Navigation Set.

BIT. Included as an integral part of the Precision Frequency Generator (PFG) is a Digital Phase Comparator which will detect an out-of-synchronization condition of the frequency divider network of the PFG. A BITE signal is generated by the computer program when an out-of-sync condition is detected. The computer will sense this condition and generate a re-synch signal to the PFG. If caused by a transient, the PFG will re-synch on command; if caused by catastrophic failure, the computer will turn on malfunction indicators on receiver-computer and on control-indicator.

3.2.2.7 Receiver-Computer Interface (See Figure 3.2-7)

The receiver-computer interface circuit consists of a phase counter, a 5-millisecond timer, an interrupt sequencer, and an accumulator buffer. The phase counter consists of a 36-bit shift register, a serial half adder, and timing counters. The register is divided into six counters of six bits each. Each of the six counters is controlled by one gate. When the gate is false, the counter is decremented by one count for each iteration while when the gate is true, the counter is incremented by one count for each iteration. Once every 5 milliseconds, each counter is emptied into the accumulator buffer. The accumulator buffer consists of an eight-bit shift register, a serial adder, and necessary controls. When one of the phase counters is emptied, its contents are shifted into the 8-bit register. A direct access to the computer memory is then initiated so as to place in the transfer buffer 16 bits of the contents of a particular memory cell. The contents of the accumulator is serially added to the contents in the transfer buffer. Another direct access of computer memory is initiated so as to store the contents of the transfer buffer in the same memory cell. The processing of the counter through this buffer is initiated by the interrupt sequencer. During the last one-third of each 5-millisecond interval, the accumulator buffer processes the six individual phase counters. At the end of the 5-millisecond period, a program interrupt of the computer is initiated. The interrupt sequencer provides the basic timing for these operations. When two-thirds of the 5-millisecond period has elapsed, the interrupt sequencer causes the accumulator buffer to start processing the first phase counter during the next iteration of the counter and process



10704

FIGURE 3.2-6 PRECISION FREQUENCY GENERATOR CIRCUIT SIMPLIFIED BLOCK DIAGRAM

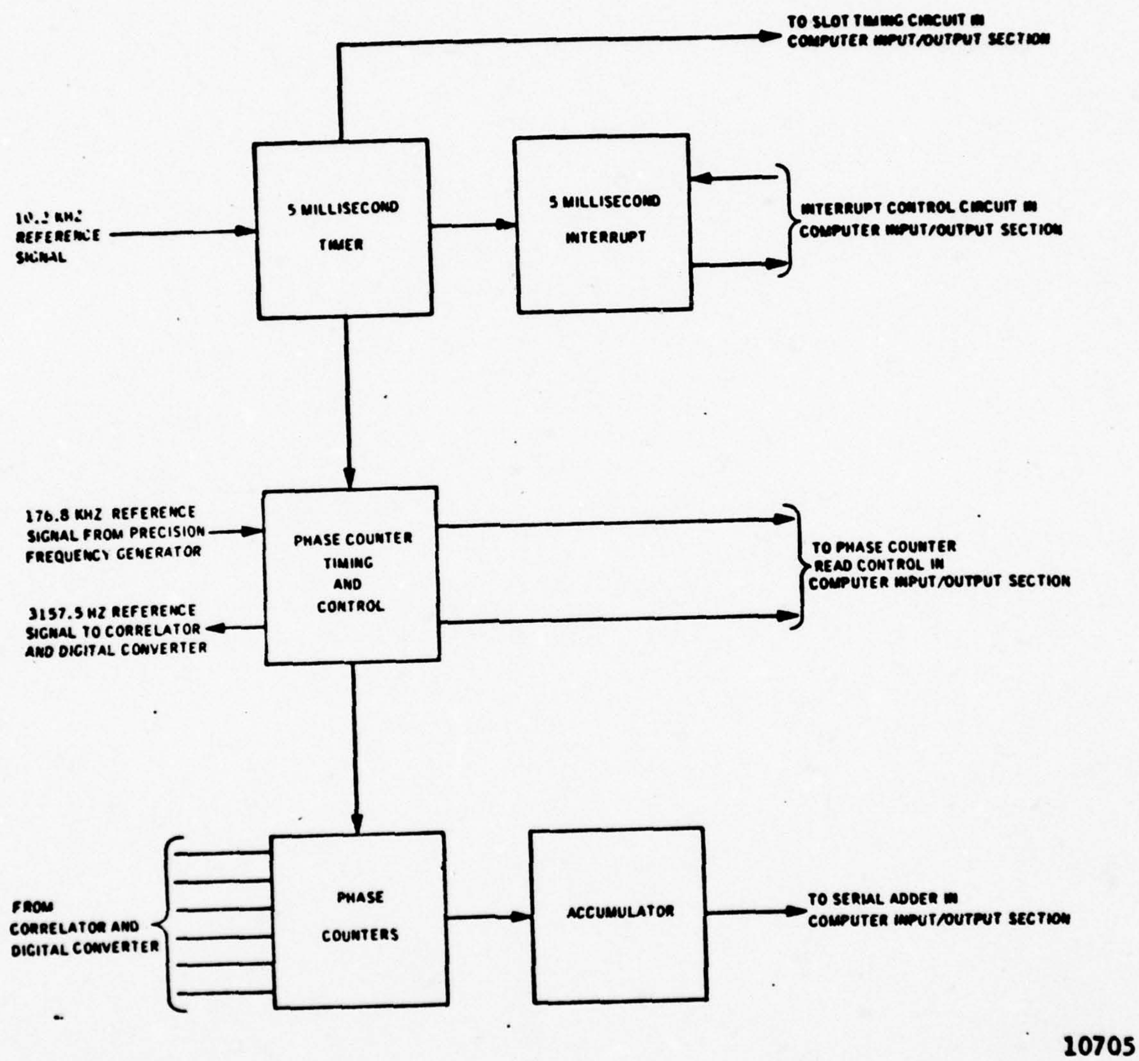


FIGURE 3.2-7 RECEIVER-COMPUTER INTERFACE CIRCUIT SIMPLIFIED BLOCK DIAGRAM

one counter during each of the following five iterations. When the 5-millisecond timer signals the end of the 5-millisecond period, a program interrupt is sent to the computer.

The I/O - Direct Memory Access (DMA) test verifies correct operation of the receiver-computer interface. A memory cell is brought out to the transfer-buffer (output of the up-down accumulator buffer) via DMA. The adder control causes the transfer buffer to be incremented by the value -1. This incremented value is returned to the original memory cell again via the DMA where the computer program is required to verify that the cell has been incremented correctly. This test, in conjunction with Phase Angle/Digital Converter and Phase Counter I/O tests, isolates malfunctions to accumulator-buffer or to receiver I/O.

3.2.2.8 Input/Output Section (See Figure 3.2-8)

The input/output section consists of an analog-to-digital converter and digital buffering circuits which enables the computer to communicate with the receiver section, OMEGA Control-Indicator, and ship's synchro inputs.

a) <u>Direct Memory Access</u>

At any time that the computer program is not accessing the computer memory, the computer's input/output section may either read 16 bits of data from a selected computer memory cell or write 16 bits of data into such a cell. Twenty microseconds must be allowed for each direct memory access. Data from the receiver, analog-to-digital converter, or control-indicator panel are transmitted to the computer by direct memory access, and data from the computer to the receiver and control-indicator panel are similarly transmitted. This transmission to and from the receiver section is controlled by periodic signals from the receiver's interrupt sequencer during the last third of each five-millisecond period. During the first two-thirds of each period, requests from the analog-to-digital converter and Control-Indicator for direct memory access are accepted. For each direct memory access, either a read or write signal is sent to the basic computer which acknowledges the signal while the memory access is being accomplished. The acknowledgement resets the read or write signal.

<u>BIT</u>. The Direct Memory Access Test is designed to check the communication link between the receiver and computer. A memory cell location is brought out to the Transfer Buffer via the DMA. The adder control causes the Transfer Buffer to be incremented by the value -1. This incremented value is returned to the original memory cell again via the DMA, where the computer verifies that the cell has been incremented correctly.

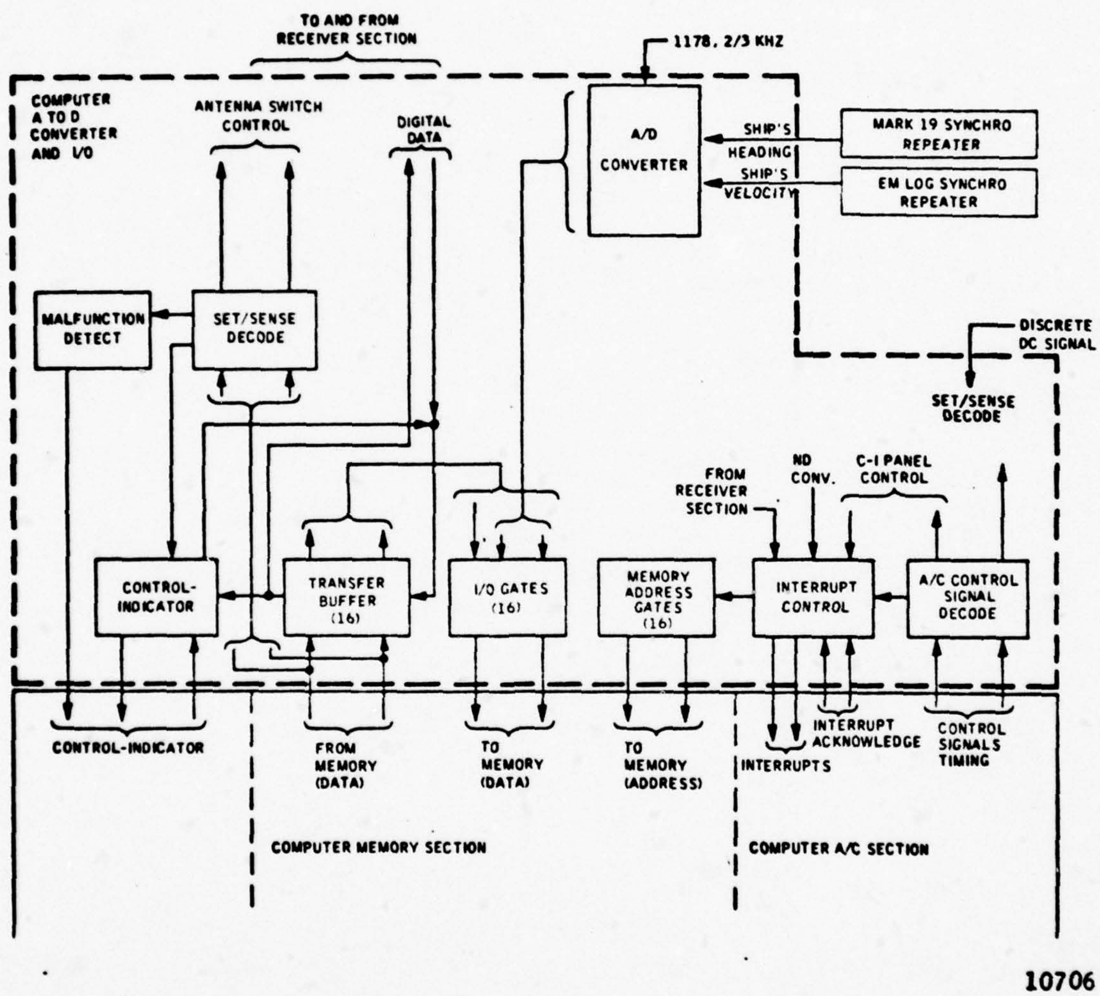


FIGURE 3.2-8 INPUT/OUTPUT CIRCUIT SIMPLIFIED BLOCK DIAGRAM

b) Analog-to-Digital Converter

The analog-to-digital converter provides a means of converting the analog inputs to digital form which will then be stored via DMA.

For synchro inputs, the input is selected by turning on the input "switches" for the desired channel. The "Electronic Scott T" converts the selected synchro signal into analog signals, one proportional to the cosine of the synchro angle and one proportional to the sine. The polarity of the sine and cosine signals is determined and used to determine the quadrant of the angle. The magnitudes of the two signals are compared to determine the half-quadrant (octant).

The input channel to be used is selected by the computer. This command controls the channel input switches and starts the timing sequence. If a synchro channel is being used, the preparation for conversion starts when the synchro reference falls to 80-percent of its normal negative peak. The required switching is performed and the hold circuit tracks their inputs until the synchro reference rises to 80 percent of its nominal negative peak. The dc voltage hold circuit then holds while the actual conversion takes place. A dual slope integrator method is used to convert the dc voltage to a binary number. The integrator is slewed for a fixed period of time by the input voltage and then slewed back to zero by the reference voltage. The length of time it takes to return to zero is proportional to the input voltage. Initially, the integrator is grounded and the capacitor is shorted by electronic switches between conversions. The input is buffered and made positive by the polarity logic which also supplies the sign bit. The positive voltage is switched into the integrator at the same time the counter is started. The integrator slews until the counter reaches full scale. At this time, the counter is reset and starts counting again while the negative reference voltage is switched to the integrator input. When the integrator output has returned to zero, the zero detector stops the counter. The counter then holds the binary equivalent of the ratio of the input voltage to the reference voltage. Thus, the binary count represents the ratio of the input to the reference scaled to binary one. When the conversion is completed, the counter and octant/polarity flip-flops hold the results until a memory access interrupt can be created to store the counter data in a predetermined DMA memory cell of the computer.

BIT The Computer I/O Test is used to test the analog-to-digital circuitry. A conversion, analog-to-digital, will be made by the Computer, digital I/O using the 400 HZ synchro reference signal as a reference. The resultant digital value will be verified by the computer program.

c) <u>Computer Program Interrupt</u>

The computer program interrupt allows the computer input/output section to force the basic computer to execute the instruction stored in the memory cell identified by the memory address lines. The instruction executed may be a "branch or save" instruction which will start a program subroutine. A period of 184 microseconds must be allowed for the maximum delay in the acknowledgement of this type of interrupt. This type of interrupt is initiated by the receiver every 5 milliseconds by the setting of a flip-flop.

<u>BIT</u>. The Program Sequence Test provides a check that the computer program is sequencing instructions and is responding to the timing signals from the receiver section. It consists of a unique discrete output instruction (SET) being given by the computer at a fixed interval of time. The instruction generates a pulse signal which is detected by an integrator type circuit. As long as the circuit continues to be 'pulsed', the output of the integrator is high (Logic 1) which indicates proper program sequencing. If the program fails to sequence or to respond to the OMEGA timing signal (5 msec interrupt), the pulses will not be generated and the output of the integrator will fall (Logic 0) indicating a failure.

d) <u>Discrete Inputs and Outputs</u>

The computer controls the system by means of "set" instructions and determines its status by means of "sense" instructions. Both of these instructions require a decoding which is partially accomplished by a common set of gates. For each instruction, 16 bits of data are available from the computer memory data register on the same lines that are used to fill the transfer register on direct memory access. One group of "set" instructions is used to control the RF sensor by specifying the switching to be performed. Another group commands and specifies an analog-to-digital conversion to be made, while the third instruction is used to inhibit interrupts, reset timers and exercise other similar control functions.

e) <u>Parallel Input/Output</u>

The parallel input or output instruction will define one word of the computer memory that either is to be loaded with data or has data to be used by external devices; this instruction is presently not used.

3.2.2.9 Memory Section

A memory cycle consists of a read and restore operation which is completed in two microseconds; 16 bits are accessed in the memory cycle. The memory cycle time is synchronous with the logic clock. The memory contents are

made non-volatile by an orderly power turn-on and turn-off procedure. When the power is first turned on and power supply voltages have come to the tolerance limits, the power supply generates a signal which causes the computer to execute a branch instruction at a specified memory cell. The instruction will start the computer program by initiating the next instruction (N) register. After execution of the first instruction, the computer cycles normally through its control states. The power shut-down procedure is initiated by the switch on the control-indicator panel or dropout detected by the power supply. In both cases, an immediate program interrupt is given to the computer. This interrupt causes the program to branch to a subroutine to store all volatile data into the memory for a possible power restore sequence before power is completely removed.

BIT. The Memory Checksum Test is provided as a test to verify the contents of computer memory. This test sums all of the permanently stored (non-volatile) contents of memory. The computer compares the sum against a predetermined value; failure to compare constitutes a failure of the test.

BIT. The Computer Memory Read/Write Test is designed to verify: 1) that the memory read/write drivers are functioning and, 2) that at least limited memory addressing is operable. This test is used when the test operator suspects that the computer memory is inoperable (i.e., memory checksum failure or inability to fill memory).

3.2.2.10 Arithmetic and Control Section

The computer section is organized as a 16-bit word machine with capabilities for 32-bit word instructions and arithmetic operations. The computer function is based on the general register approach. The arithmetic and control section consists of general registers, multiple shift unit, arithmetic unit, B register, A register, N register, W register, and clock generator.

BIT. The Computer Logic Test is designed to verify that the arithmetic and control section of the computer hardware is functioning in a normal manner. This test consists of execution of the basic instructions of the computer being executed and being checked for proper bit patterns in appropriate registers. Upon completion of this a "sample problem" is executed, primarily using the ARCTAN routine of the normal program storage. This routine was selected because it uses about 90% of the instruction repertoire of the computer.

BIT. The program sequence test is also used in conjunction with the arithmetic and control section. The test is used to insure that the computer program is sequencing properly. If not, then the A and C section is suspect. This test is fully described in paragraph 3.2.2.8(c).

3.2.2.11 Power Supply Section

The power supply section provides a means of providing regulated +16, +21, +5, -6, -12, -16, and -25 volt dc outputs. All but the -12 volt dc are required for computer section operation while the receiver section requires +12, -12, and +5 volt dc for its operation. The power supply section consists of an RF filter, full-wave rectifier assembly, pre-regulator, dc-to-dc converter, protection circuit, and turn-on and turn-off sequencing circuits.

The sequencing circuits provide logic signals for orderly turn-on and turn-off of the computer. Sufficient power storage is provided to insure an orderly shutdown whenever a loss of power is encountered.

Power Supply BITE. The BITE associated with the power supply consists of level detectors of each of the six power supply outputs. The outputs of the level detectors are fed to an 'AND' gate. The output of this 'AND' gate will remain high as long as the power supply outputs remain within the tolerance limits. The output of the gate will go to ground level in the event of a failure. This signal will then be used to turn off the power supply to prevent further damage to the assembly. The Power Supply Malfunction Indicator will be lighted for any power supply malfunction and will remain lighted until the system ON/OFF select switch is returned to the power OFF position.

3.2.2.12 OMEGA Control Indicator (See Figure 3.2-9)

The OMEGA Control-Indicator provides a means of initiating various programs, requesting specific information for display, monitoring status of the system, and displaying current computed navigational data. The Control-Indicator consists of controls and indicators, input and output shift registers, input control logic, decoders, and dimmer control.

The Submarine OMEGA Navigation Set is energized by actuating the POWER switch. Previously the Interface Box switches must be on—C/I Power, Rec/Comp Power, and Oscillator HTR PWR. This enables the power supply circuit and prepares the system for operation. After initial programmed tests have been completed, system operation can be initiated by pressing the INSERT or DISPLAY switch-indicator. The system can be initiated only when these indicators are illuminated. The INSERT or DISPLAY indicators will not be illuminated during an operation but will automatically illuminate whenever an operation is completed. During insert, the operation is completed when the operator presses the ACCEPT switch-indicator. When data is inserted, the information generated by pressing specific keyboard switch-indicators is shifted from the input shift register into the computer. This information can be observed on the front panel displays. During the display mode, pressing specific keyboard switch-indicators will instruct the computer to

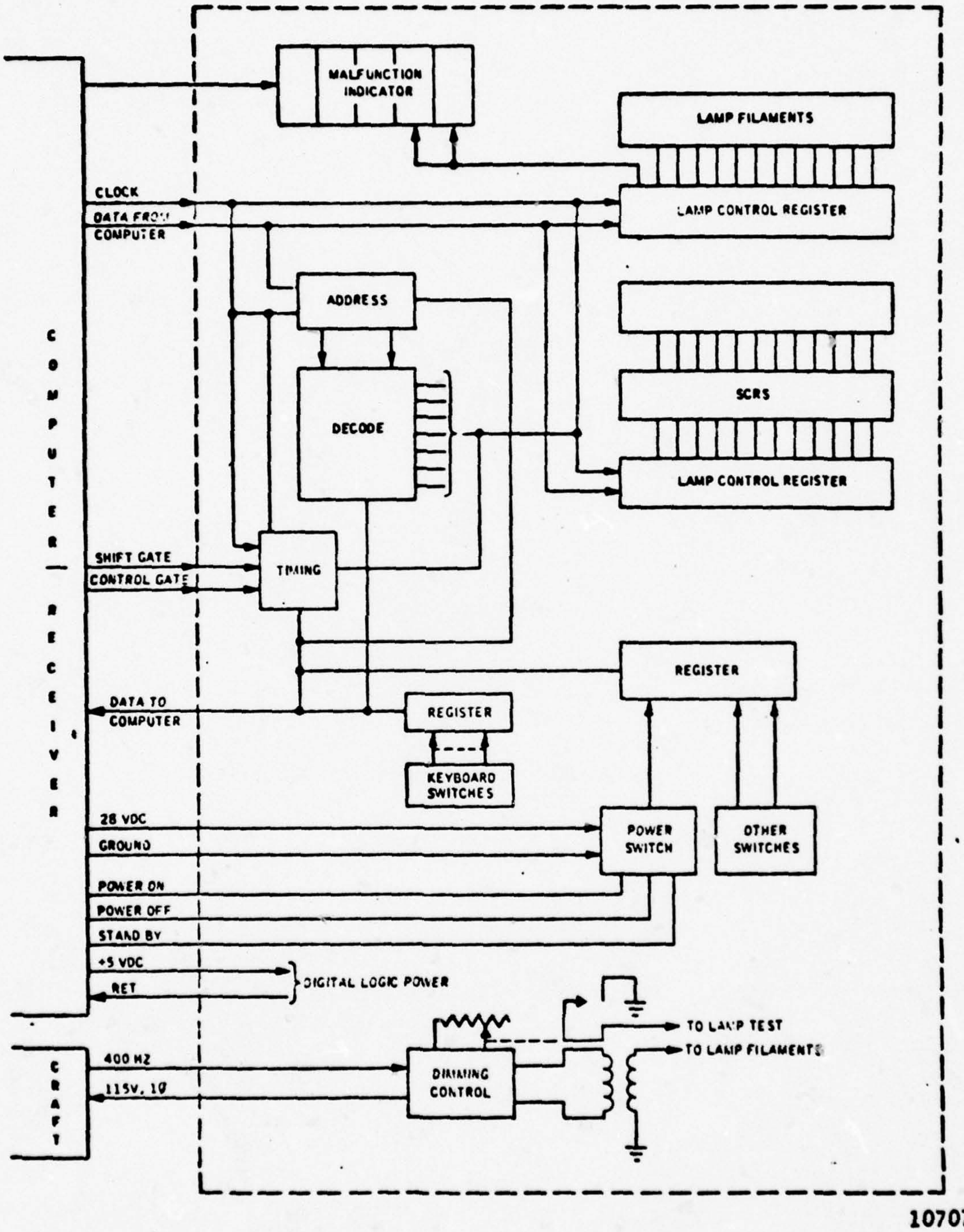


FIGURE 3.2-9 CONTROL-INDICATOR ASSEMBLY SIMPLIFIED BLOCK DIAGRAM

provide the control-indicator with specific information. This information is then transferred through the input logic circuit to the output shift register. The output from the output shift register is supplied to the decoder where the digital information is decoded and displayed on the front panel. The intensity of the front panel indicators is controlled by the dimmer control circuit. The potentiometer in the dimmer control circuit is used to vary the load of the rectifier circuit. Varying the load also varies the voltage supplied to the indicators. Detailed operation using the OMEGA Control-Indicator is provided in Section 3.2.4.3.

BIT. The Control-Indicator Panel Test is intended for use as a fault isolation between the Receiver-Computer and the C-I panel. Upon demand of the operator, the computer will cause the indicators and segmented displays (lamp filaments) to be turned ON for a period of 10 seconds. This test will override any other display data and upon completion of the 10-second period, the panel reverts to the quiescent state.

3.2.3 Computer Input/Output

3.2.3.1 Introduction

The purpose of this section is to provide the information required to program the Submarine OMEGA Navigation Set and related Factory Checkout Equipment.

The first part of this section describes those aspects of the computer that relate to communication between the computer and external devices. The second describes the programmable aspects of each device or function that interfaces with the computer section.

3.2.3.2 Computer Input/Output Description

Communication between the computer and external devices is by means of programmed I/O (discretes and parallel input/output), Computer Interrupts or Direct Memory Access. A general capability for each technique is mechanized in the computer. The particular method utilized and the significance of the data transferred are dependent on the design of the external devices.

A description of each technique is given in this section.

Table 3.2-2 contains a map of the 1070 Computer Memory as used in the Submarine OMEGA System. It shows the area of memory reserved for use by those I/O techniques requiring fixed memory location.

a) Programmed Input/Output

The computer program can control communications between the computer and external devices through use of the five (5) Input/Output instructions. Each of these I/O instructions contains from five (5) minimum to sixteen (16) maximum bits of data that the computer will make available to external devices whenever an I/O instruction is executed. The external device can then decode these bits to determine which device the bits are directed to and what action is required. The device will also be able to detect which of the five (5) instructions is being executed. The appropriate device can take the required action which includes the setting or resetting of the low and zero indicators of the computer (which can be sensed by the computer program).

In addition, two (2) of the five (5) instructions will address a particular word in the computer memory, the contents of which can be made available to external devices or loaded from data provided by the external devices.

TABLE 3.2-2

1070 - FIXED MEMORY LOCATIONS

MEMORY WORD (Hexadecimal)	MEMORY UTILIZATION
0000	SPARE[a]
0001	INPUT - C & I Panel Miscellaneous Switches
0002	INPUT - C & I Panel Keyboard Switches
0003	OUTPUT - C & I Panel Left Display Digits 6-3
0004	OUTPUT - C & I Panel Left Display Digits 2-1
0005	OUTPUT - C & I Panel Right Display Digits 6-3
0006	OUTPUT - C & I Panel Right Display Digits 2-1
0007	OUTPUT - C & I Panel Left Alpha Numeric and Punctuation
0008	OUTPUT - C & I Panel Right Alpha Numeric and Punctuation
0009	OUTPUT - C & I Panel Miscellaneous Lamps Output
000A	SPARE[a]
000B	OUTPUT - C & I Panel Lamps, Keyboard Upper Left
000C	OUTPUT - C & I Panel Lamps, Keyboard Upper Right
000D	OUTPUT - C & I Panel Lamps, Keyboard Lower
000E	SPARE[a]
000F	SPARE[a]
0010	Phase Counter - Test
0011	Phase Counter - Cosine 10.2 kHz
0012	Phase Counter - Sine 10.2 kHz
0013	Phase Counter - Cosine 13.6 kHz
0014	Phase Counter - Sine 13.6 kHz
0015	Phase Counter - Cosine 11.1/3 kHz
0016	Phase Counter - Sine 11.1/3 kHz
0017	Direct Memory Access Test
0018	A/D Converter - Channel 0 (unused)
0019	A/D Converter - Channel 1 (unused)
001A	A/D Converter - Channel 2 (Heading, Mark 19 Repeater)
001B	A/D Converter - Channel 3 (Submarine Speed, E.M. Log Repeater)

TABLE 3.2-2 (Continued)

MEMORY WORD (Hexadecimal)	MEMORY UTILIZATION
001C	A/D Converter - Channel 4 (BITE excitation test)
001D	A/D Converter - Channel 5 (unused)
001E	A/D Converter - Channel 6 (unused)
001F	A/D Converter - Channel 7 (unused)
0020	OUTPUT - Receiver 10.2 kHz, Antenna switching
0021	OUTPUT - Receiver 13.6 kHz, Antenna switching
0022	OUTPUT - Receiver 11.33 kHz, Antenna switching
0023	OUTPUT - Test and Miscellaneous
0024 - 003F	Serial data inputs/outputs
0080 - 00FF	Extended Addressing Area
0102 - 010F	Pin Routine Addresses
0140	Computer START Address (Power On)
0142	Power Dropout Interrupt Address
0144	Support Equipment Interrupt Address
0146	Five Millisecond Interrupt Address
0148	C & I Panel Input Interrupt Address
0156	Serial Data Input Interrupt Address

[a]These locations are read by the C & I Panel but not decoded. They are available for program storage.

Locations 00, 30, 3F are reserved for excess data dumps.

b) Computer Interrupts

The occurrence of particular events can be signaled to the computer by interrupting the normal sequence of executing instructions. These interrupts can be generated by the special I/O to signal the passing of five (5) milliseconds of time or a control and indicator panel input, by the computer to identify a power dropout, or by the support equipment.

When the computer receives an interrupt signal, it takes the next instruction from the unique address associated with the particular interrupt (see Table 3.2-2) instead of taking it from the address specified in the next instruction address (NIA) register. This allows one instruction to be executed out of sequence and the following instruction to be taken from the original sequence unless the out of sequence instruction changes the next instruction address register (such as BUC or a BSV). No extra time is required for executing an interrupt. If an instruction is in execution at the time the interrupt request is received, it is completed before the interrupt is processed. Interrupt requests arriving during the execution of a BSV, IOC or XEQ instruction are inhibited until an instruction that is not a BSV, IOC or XEQ is executed.

The interrupts generated by the special I/O and the support equipment may be inhibited by setting the interrupt inhibit flip-flop with an LGC instruction. This flip-flop is also set true by a program start signal. If an LGC instruction that changes the state of the inhibit flip-flop is being executed at the time an interrupt request is being received, the state of the flip-flop at the completion of the execution of the instruction controls the interrupt. If more than one interrupt request is received by the computer at one time, the highest priority interrupt is the power-off interrupt (which cannot be inhibited) followed by the special I/O and then the support equipment interrupts.

If the program is to execute a special subroutine when an interrupt occurs, a BSV instruction should be loaded into the unique location associated with the particular interrupt. The operand of the BSV instruction would be the address of the first word of the special subroutine. The execution of the BSV instruction would preserve the reentry point in the original sequence of instructions (where the interrupt occurred) and the program flags. This will permit the program to reenter the original sequence by executing a BBK instruction at the conclusion of the special subroutine. If other interrupts are to be inhibited during the execution of the special subroutine (power shutdown routine for example), the first instruction of the routine must set the inhibit flip-flop true. It should be reset when interrupts can be accepted again.

c) Direct Memory Access

The computer has been designed to allow the special I/O to communicate directly with the computer memory. This capability exists only with a preselected block of memory words (see Table 3.2-2) and includes both input and output.

The significance of the data, the timing of the transfer and the amount of data are entirely dependent on the design of the special I/O. It is only used for communication with the Submarine OMEGA System and not with support equipment associated with the computer.

The transfer of data to and from the memory can be inhibited by setting the DMA inhibit flip-flop with the LGC instruction. This flip-flop is true when the program start signal is given.

3.2.3.3 Programming Data

This section provides the necessary programming data for each device or hardware function that the Submarine OMEGA programmer will have to be concerned with.

a) Control and Indicator Panel (C & I)

Communication between the computer and the C & I Panel (see Figure 3.2.13) is handled by the Special I/O. Sixteen (16) words of Direct Memory Access have been set aside for this purpose (see Tables 3.2-2 and 3.2-3. The communication is processed in synchronization with the five (5) millisecond time mark coming from the receiver. The five (5) millisecond period is divided into three (3) equal parts starting at the mark and all C & I communications occur during the middle one-third of a period. The outputs to the panel are cycled every eighty (80) milliseconds with a single word sent to the panel every five (5) milliseconds for a total of sixteen (16) words (not all words are decoded by the panel logic). Inputs are cycled every ten (10) milliseconds with one sixteen (16) bit word brought into memory each five (5) milliseconds.

The two (2) input words are brought into words one and two (2) of DMA and are part of the sixteen (16) words picked up and sent to the panel. The bits of each input word will be zero unless a button had been depressed during the last ten (10) milliseconds (unused bits are always zero). The bit (bits) corresponding to the button (buttons) depressed will be true. Whenever an input word contains a one, an interrupt will be generated in the computer and the instruction located at 0148_{16} will be executed. The program will then have ten (10) milliseconds to read the input words and determine which button has been depressed. If interrupts are inhibited, the interrupt will occur when interrupts are enabled. However, if more than ten (10) milliseconds have passed, it will not be possible to determine which button was depressed.

The five (5) millisecond interrupt always takes priority over the C & I panel interrupt. They can only occur at the same time if interrupts have been inhibited for some period of time. Bit thirteen (13) of DMA word 23_{16} must be set to allow interrupts from the special I/O, otherwise they are inhibited.

TABLE 3.2-3 CONTROL AND INDICATOR PANEL DMA IMAGE

(WORD) 16	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	DESCRIPTION
	BIT POSITION																
0									NOT USED								
1															FLOAT LOOP	PNL TEST	MISCELLANEOUS SWITCH INPUT
2	HOLD	CLEAR DIS-PLAY	INSERT ACCEPT	RZ/E COH	SHP/ N POS	AUTO BRG/ RN6	9	8	7	6	5	4	3	2	1	0	KEYBOARD SWITCH INPUT
3		DIGIT #6				DIGIT #5				DIGIT 4				DIGIT #3			LEFT DISPLAY
4		DIGIT #2				DIGIT #1						NOT USED					LEFT DISPLAY
5		DIGIT #6				DIGIT #5				DIGIT 4				DIGIT #3			RIGHT DISPLAY
6		DIGIT #2				DIGIT #1						NOT USED					RIGHT DISPLAY
7		PUNCTUATION							NOT USED			ASC II CODE					LEFT ALPHA NUM & PUNCTUATION
8		PUNCTUATION							NOT USED			ASC II CODE					RIGHT ALPHA NUM & PUNCTUATION
9	EP	ET	SYNC	HOLD	INSERT	ACC	DISP	CLEAR	SIG LOSS	AMB	LOOP	POS UNC	FLT		NOT USED		MISCELLANEOUS LAMPS OUTPUT
B		NOT USED		RZ	SHIP	AUTO	9	8	7	6	5	4	3	2	1	0	UPPER LEFT KEYBOARD LAMPS
C		NOT USED		E	N	W	MAN	H	G	F	E	D	C	B	A	S	UPPER RIGHT KEYBOARD LAMPS
D		NOT USED		COH	POS	BRG/ RNG	AUTO H/S	MAN H/S	CAL H/S	LOP	DT/ GMT	CSE ETE	NCTR	VAR	STA-TUS	IN-PUTS	LOWER KEYBOARD LAMPS
A									NOT USED								
E									NOT USED								
F									NOT USED								

The output to the C & I Panel is controlled by the bits in the DMA words. The program may write into these words at any time, independent of the rate at which the DMA words are transmitted to the panel. The first, fourteenth fifteenth and sixteenth words are spares and available for program storage. The second and third words are used for inputs to define which buttons have been depressed. Words three (3) through six (6) control the characters displayed in the left and right display registers. Table 3.2-4a gives the resulting display for each hexadecimal character used to control each digit of the display.

Words eight (8) and nine (9) define (see Table 3.2-4b) the punctuation for the left and right display registers and the legend (see Table 3.2-5) to be displayed in the left and right legend display. The remaining words control the lamps located behind the buttons and status indicators on the panel. If a bit is a one, the corresponding lamp is on. Otherwise, the lamp is off.

Whenever control is to be given to the remote C & I Panel, bit sixteen (16) of DMA word 23_{16} must be set to one. When this bit is zero the master C & I Panel has control. Only the panel in control can provide inputs to the computer.

b). Phase Counters

DMA words 10_{16} through 16_{16} receive the seven (7) phase counter inputs as shown in Table 3.2-2.

The test word will count up if bit 4 of word 23_{16} is a one and down if the bit is a zero. The maximum input to the sine and cosine words is twelve (12) counts per five (5) milliseconds. The value contained in these words can be interpreted as counts as a function of the sine or cosine of the phase angle.

These words are updated every five (5) milliseconds with the update occurring during the last one-third of the five (5) millisecond period that is initiated by the time signal from the receiver. The update consists of reading a word from DMA, adding the output of the phase counter and writing the new word back into DMA. This requires approximately 181 microseconds from the read to the write operation. The LSB for all updating is bit one.

Word 17_{16} of DMA is a test word that is decremented by one count seven (7) times per five (5) milliseconds when the DMA test has been selected by posting a one in bit 13 of DMA word 23_{16}. During test, words 10_{16} through 16_{16} are not updated.

c) A/D Conversion

DMA words 18_{16} through $1F_{16}$ receive inputs from the Analog to Digital Converter. One word is brought in during the last one-third of each five (5) millisecond period, with all right words cycled every forty (40) milliseconds.

TABLE 3.2-4a DISPLAY REGISTERS - CHARACTERS

ASCII BITS 7 5 4 3 2 1	SYMBOL	ASCII BITS 7 5 4 3 2 1	SYMBOL
0 0 0 0 0 0	Blank	1 0 0 0 0 0	ˇ
0 0 0 0 0 1	!	1 0 0 0 0 1	A
0 0 0 0 1 0	"	1 0 0 0 1 0	B
0 0 0 0 1 1	#	1 0 0 0 1 1	C
0 0 0 1 0 0	$	1 0 0 1 0 0	D
0 0 0 1 0 1	%	1 0 0 1 0 1	E
0 0 0 1 1 0	°	1 0 0 1 1 0	F
0 0 0 1 1 1	·	1 0 0 1 1 1	G
0 0 1 0 0 0	(	1 0 1 0 0 0	H
0 0 1 0 0 1	)	1 0 1 0 0 1	I
0 0 1 0 1 0	*	1 0 1 0 1 0	J
0 0 1 0 1 1	+	1 0 1 0 1 1	K
0 0 1 1 0 0	,	1 0 1 1 0 0	L
0 0 1 1 0 1	—	1 0 1 1 0 1	M
0 0 1 1 1 0	.	1 0 1 1 1 0	N
0 0 1 1 1 1	/	1 0 1 1 1 1	O
0 1 0 0 0 0	0	1 1 0 0 0 0	P
0 1 0 0 0 1	1	1 1 0 0 0 1	Q
0 1 0 0 1 0	2	1 1 0 0 1 0	R
0 1 0 0 1 1	3	1 1 0 0 1 1	S
0 1 0 1 0 0	4	1 1 0 1 0 0	T
0 1 0 1 0 1	5	1 1 0 1 0 1	U
0 1 0 1 1 0	6	1 1 0 1 1 0	V
0 1 0 1 1 1	7	1 1 0 1 1 1	W
0 1 1 0 0 0	8	1 1 1 0 0 0	X
0 1 1 0 0 1	9	1 1 1 0 0 1	Y
0 1 1 0 1 0	:	1 1 1 0 1 0	Z
0 1 1 0 1 1	;	1 1 1 0 1 1	[
0 1 1 1 0 0	<	1 1 1 1 0 0	\
0 1 1 1 0 1	=	1 1 1 1 0 1	↗
0 1 1 1 1 0	>	1 1 1 1 1 0	▲
0 1 1 1 1 1	?	1 1 1 1 1 1	▩

TABLE 3.2-4b DISPLAY REGISTERS - PUNCTUATION

CODE	DISPLAY
BIT 16 = 1	degree marker to upper right of digit 4
BIT 15 = 1	decimal point to lower right of digit 3
BIT 14 = 1	decimal point to lower right of digit 2
BIT 13 = 1	degree marker to upper right of digit 1

TABLE 3.2-5 LEGEND DISPLAYS

LEFT DISPLAY	CODE	RIGHT DISPLAY
A	BIT 1 = 1	A
B	BIT 2 = 1	B
C	BIT 3 = 1	C
D	BIT 4 = 1	D
E	BIT 5 = 1	E
F	BIT 6 = 1	F
G	BIT 7 = 1	G
H	BIT 8 = 1	H
N	BIT 9 = 1	E
S	BIT 10 = 1	W
MIN	BIT 11 = 1	R
.KNOTS	BIT 12 = 1	L

NOTE: Temperature problems will occur if more than two legends are displayed simultaneously for a significant length of time.

On the submarine DMA word 1F contains the true heading input and word 1E contains the ship's log input. Each of these inputs is from a synchro with either a tangent or cotangent in bits 1 to 10 of the input word. These bits define the synchro input within a single octant (45 degrees). Bits 11 to 13 of the input word define the correct octant. The first octant is 0 and bit 11 true defines the second octant. Bits 1 to 10 represent a tangent for octants 0, 2, 4, and 6; otherwise they contain a cotangent.

Word 1F converts directly to true heading. Word 1E is shifted 120° from zero so that it is necessary to subtract 120° from the synchro value before converting to velocity. The conversion factor is 40 knots per 360°.

Word $1C_{16}$ is an analog-to-digital converter test word which will receive a fixed input every cycle. This input is nominally a $01E6_{16}$.

Words 1A and 1B contain the reference excitation voltage for the heading and velocity synchro, respectively and are tested as part of the BIT programs.

d) Discrete Inputs

Discrete inputs are available for input to the program. There are six 28 volt discrete inputs and one 5 volt discrete input. Discrete inputs 3 and 4 (28V) represent the presence or absence of the synchro excitation voltage, respectively. These discretes are acknowledged under program control during SET, SENSE, or IOC commands. True state (0) indicates voltage ≤ 9 volts, and false state (1) indicates voltage ≥ 13 volts.

e) Precision Frequency Generator

The Precision Frequency Generator provides an accurate time signal to the special I/O every five (5) milliseconds. It also provides accurate time signals to logic in the receiver and phase to digital converters. A BITE signal (Precision Frequency Generator No-Good) is available that can be sensed by the program (SNS 0050) which indicates that inconsistencies have been detected in the countdown circuits of the generator. Execution of a SET 000A will reset the countdown logic of the Precision Frequency Generator to an initial state.

The five (5) millisecond signal causes the special I/O to initiate countdown logic that will result in the DMA input and output described in other sections. In addition, the computer will be interrupted by the special I/O and the instruction located at word 0146_{16} will be executed. The interrupt can be inhibited by setting bit 12 of DMA word 23_{16} to zero or setting the interrupt inhibit flip-flop in the computer. If the interrupt signal becomes true while the inhibit is on the interrupt will occur as soon as the inhibit is removed. Inhibiting the interrupt will not cause the special I/O to delay in initiating the DMA input and output.

f) Program Monitor Signal

The program must execute a SET 000C at least every 80 milliseconds or the system malfunction lamp on the C & I Panel will be turned on. This will assure that a malfunction will be indicated if the program fails to execute the SET instruction due to either a programming error or a computer failure.

g) Antenna Select

DMA words 20_{16}, 21_{16}, and 22_{16} control the antenna and calibrate signals that are routed into the 10.2 kHz, 13.6 kHz, and 11.33 kHz receivers respectively. Table 3.2-6 gives the bit position, mnemonic and function for each signal. These words are accessed once every five (5) milliseconds.

TABLE 3.2-6

ANTENNA SELECT OUTPUT SIGNAL FORMAT

Bit	Mnemonic	Function
1	R(X)A	Antenna loop A (Floater)
2	R(X)AQ	Antenna loop A - 90°
3	R(X)B	Antenna Loop B
4	R(X)AB	Antenna loop - B
5	R(X)TQ	Calibrate/Test (inverted)
6	R(X)T	Calibrate/Test
7	I C(X)	Inverse
8-16	---	Unused

h) Test

DMA word 23_{16} controls the selection of system tests plus other miscellaneous signals that have previously been discussed. Table 3.2-7 defines the significance of each bit of the word. This word is accessed by the special I/O once every five (5) milliseconds.

TABLE 3.2-7 DMA TEST SELECT WORD FORMAT

Bit*	Function
1	Not used
2	Not used
3	Phase Angle to Digital Converter Test
4	Phase Counter I/O Test
5	Not used
6	Not used
7	Not used
8	Not used
9	Receiver/Computer No-Go (bit 9 = 0)
10	System Malfunction (bit 10 = 0)
11	Antenna Coupler Malfunction Indicator
12	Allow special I/O interrupts
13	Input/Output - DMA Test
14	Not used
15	Not used
16	Not used

*unless otherwise indicated the specified bit is value 1 for True condition.

The Receiver/Computer NO-GO signal will be posted if the program detects a system problem that can be isolated to the Receiver-Computer. This will turn on a lamp on the Receiver-Computer box that must be manually reset. As long as this lamp is on,the SYSTEM lamp on the C & I Panel will be illuminated. The System Malfunction bit will be posted by the program any time a system malfunction is detected. The SYSTEM lamp on the C & I Panel will also be illuminated when this signal is given. In addition, the SYSTEM lamp will be illuminated if the hardware detects a failure in the basic computer clock or if the Program Monitor signal is not given every eighty (80) milliseconds by the program.

3.2.4 Operation

3.2.4.1 Performance and Functions of Equipment

A fully implemented OMEGA system consists of eight very low frequency (VLF) OMEGA transmitting stations. The eight VLF OMEGA transmitting stations provide a worldwide electronic lattice, within which the position of the craft can be determined within one or two miles on a worldwide basis. The OMEGA Navigation set utilizes the transmitted OMEGA signals along with submarine and programmed navigational data to provide continuous navigational displays to assist in determining the submarine present position. Updated data can be inserted by manipulating the controls provided on the OMEGA Control-Indicator panel. The controls on the OMEGA Control-Indicator panel can also be used to select specific navigational data for display. Detailed operational functions are provided in paragraph 3.2.5.

3.2.4.2 Functions of Operating Controls and Indicators

3.2.4.2.1 OMEGA Receiver-Computer. (See Figure 3.2-10) - Table 3.2-8 lists the function of each indicator on the OMEGA Receiver-Computer front panel.

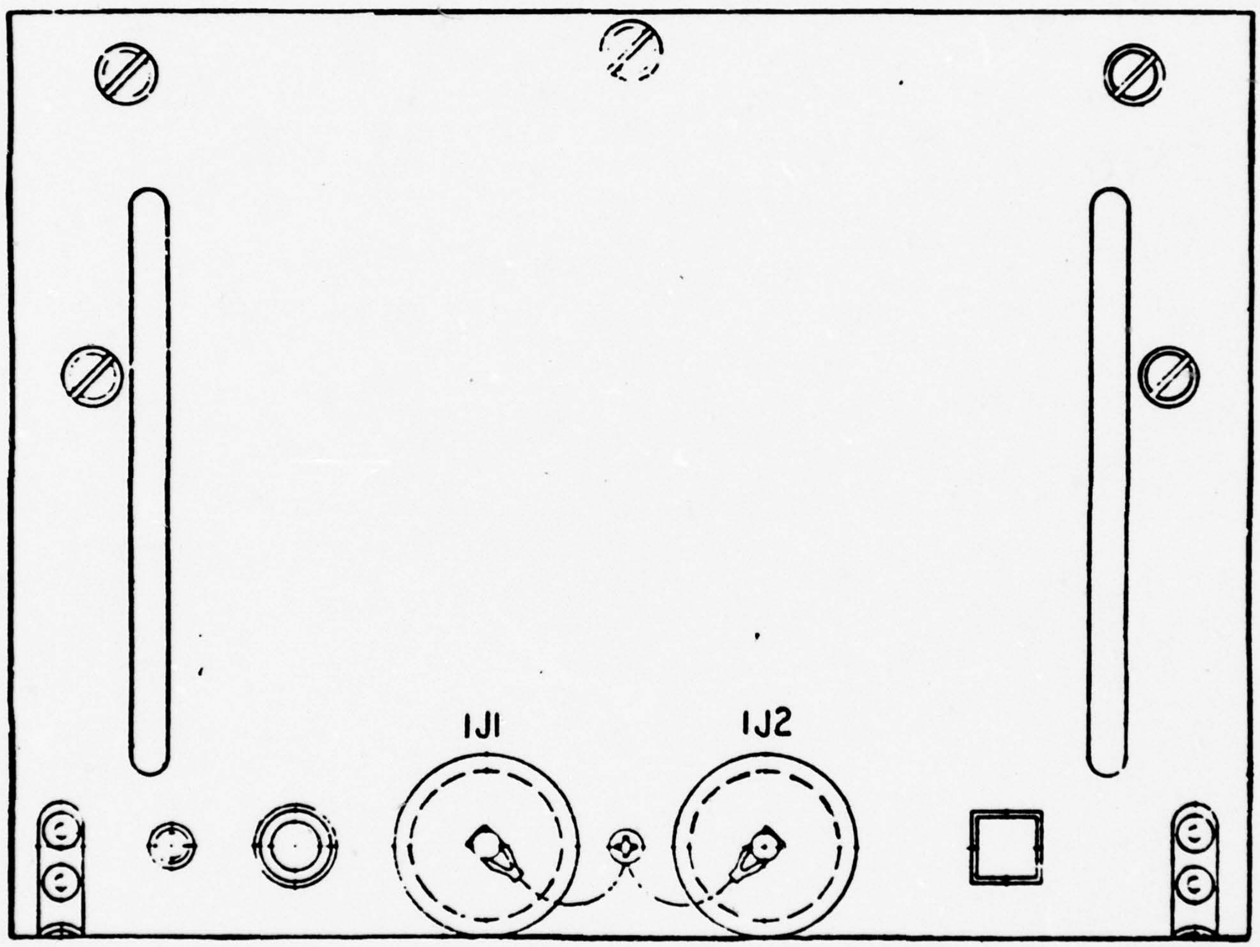


FIGURE 3.2-10 OMEGA RECEIVER-COMPUTER OPERATING INDICATOR

TABLE 3.2-8 OMEGA RECEIVER-COMPUTER INDICATORS

Panel Marking	Type of Device	Function
PWR MALF	Lamp Indicator	To illuminate when any malfunction is present in the OMEGA Receiver-Computer power supply circuit. The indicator will remain on until malfunction is corrected.
BITE	Mechanical Flag	Flag is red when any of the following tests fail during self test: 1. Program sequence test. 2. Basic timing signals from the receiver section. 3. RF test. 4. Phase-to-Digital test. 5. G.P. self test. 6. Memory checksum. 7. Computer input/output 8. DMA test. 9. Phase Counter test. NOTE: Once the indicator is illuminated (red and white), the indicator will remain in that state until reset manually. The indicator can be reset by rotating the indicator. When reset, the indicator will appear all white. The BITE indicator must be reset with power off to ensure no failures.
	Elapsed time indicator	Indicate equipment operation in hours.

3.2.4.2.2 OMEGA Control-Indicator. (See Figure 3.2-11) - Table 3.2-9 lists the function of each control and indicator on the OMEGA Control-Indicator panel.

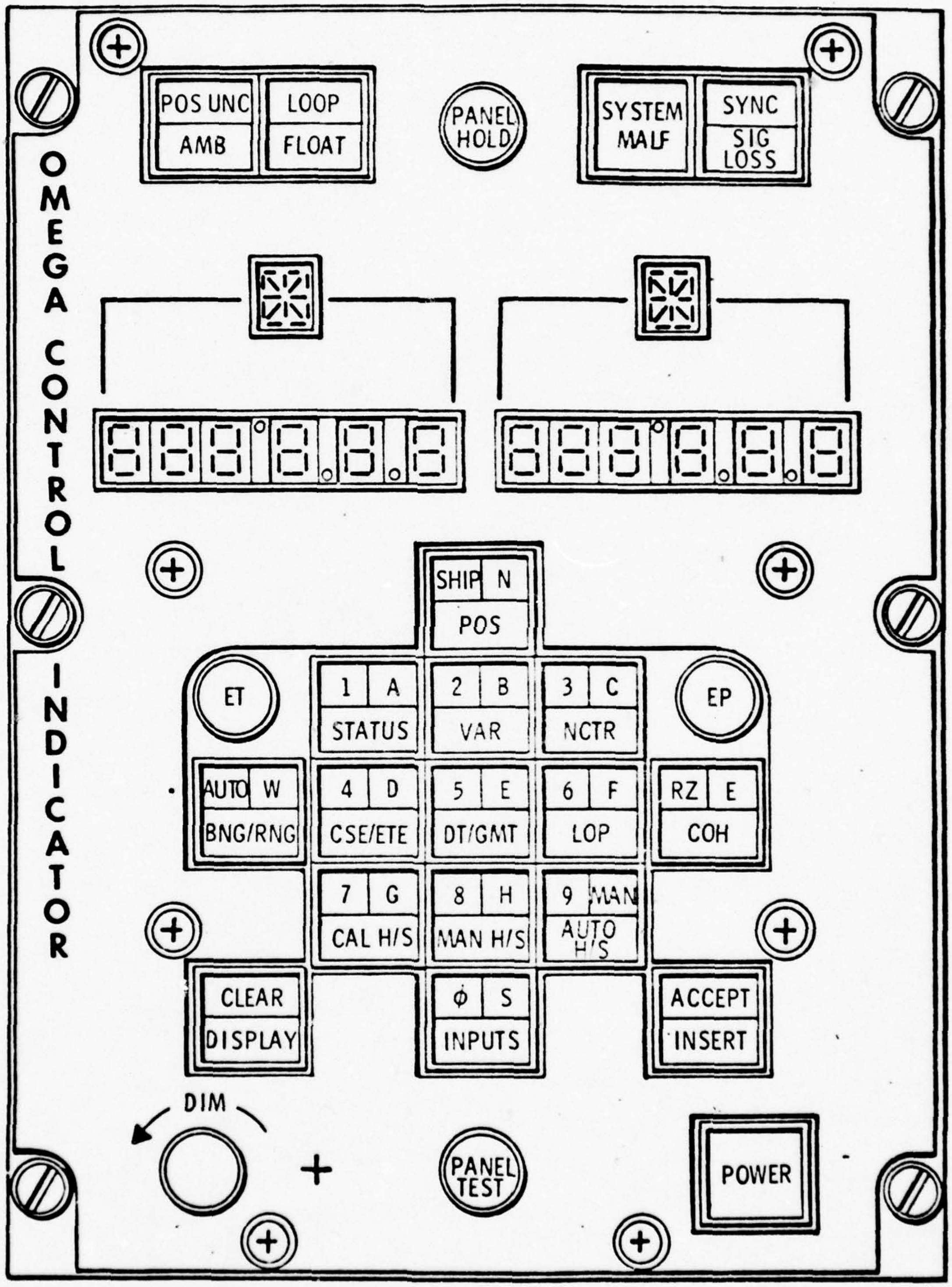


FIGURE 3.2-11 OMEGA CONTROL AND INDICATOR PANEL

TABLE 3.2-9 OMEGA CONTROL-INDICATOR OPERATING CONTROLS AND INDICATORS

Panel Marking	Type of Device	Function
LOOP FLOAT	Switch-Indicator	The illuminated portion, either LOOP or FLOAT, indicates the type of antenna which is being accepted and processed by the Receiver-Computer. Depressing this switch will cause the indication to toggle to the other indication. It is the operator's responsibility to inform the Omega receiver which antenna is being utilized.
POS UNC	Indicator lamp	This is the position uncertainty indicator which tells the operator that the program has gone into the difference frequency mode to resolve lanes. The system can be in error by as much as 36 N.M. in this mode. This indicator will always be illuminated when a "B" or "C" fix is inserted. It should go out in less than 5 minutes if enough OMEGA information is being received.
AMB	Indicator Lamp	This is the OMEGA ambiguity indicator which informs the operator that more than one state vector exists in the position solution calculations. Normally this implies that signals from one station are in error or the system is receiving insufficient information to completely define its present position.
SIG LOSS	Indicator Lamp	This is the signal loss light which illuminates when OMEGA signals are lost. This light will normally illuminate when the ship's antenna coupler is not providing signals to the OMEGA receiver or when the ship is submerged.
SYSTEM MALF	Indicator Light	Illuminate when error and/or out of tolerance conditions is present during self test. Items 1 thru 10 under BITE in Table 3.2-9 and Interface Box Pre-Amp Test, synchro Excitation Test, Scale Factor Test & Bias Test will illuminate this Indicator.

TABLE 3.2-9 OMEGA CONTROL-INDICATOR OPERATING CONTROLS AND INDICATORS (Continued)

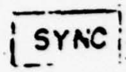
Panel Marking	Type of Device	Function
	Indicator Light	Illuminate when system is in synchronization mode.
	Switch Indicator	Initiate panel test which illuminates all panel indicators and readout in a predetermined manner.
	Left Alphanumeric Display	Indicate OMEGA station (A, B, C, D, E, F, G, or H), or hemisphere (N or S).
	Right Alphanumeric Display	Indicate OMEGA station (A, B, C, D, E, F, G, or H), hemisphere (E or W).
	Left and Right Segmented Displays	Indicator 6 digits, decimal, and degree sign.
	Potentiometer	Vary intensity of the front panel indicators.
	Switch-Indicator	In the HOLD mode, the following displayed data will be stored at the time this mode is entered and will not be updated until the return to the normal mode. In the normal mode, all displayed data changes at its normal update rate. 1. Craft Position (POS)(SHIP) 2. Calculated Speed and Track Angle. (CAL H/S) 3. MK-19 heading and Ships EM log Inputs. (AUTO H/S). 4. Bearing and Range Between Selected Destinations(BRG/RNG) 5. Course - Estimated Time to Selected Destinations (CSE/ETE) 6. Date - Greenwich Mean Time (DT/GMT)

TABLE 3.2-9 OMEGA CONTROL INDICATOR OPERATING CONTROLS AND INDICATORS (Continued)

Panel Marking	Type of Device	Function
POWER	Switch	This switch controls application of system power. When off, the button is mechanically in a raised condition. When it is momentarily depressed, (button remains flush to the panel surface) there is no illumination of this switch and the computer power supply is energized and power is applied to the whole system. The computer then goes through an automatic turn-on sequence and into a computational mode selected by the panel.
CLEAR / DISPLAY	Switch-Indicator	The illuminated CLEAR enables the operator to initiate the panel quiescent state so that a new Control panel "Display" or "Insert" sequence can be started. The illuminated DISPLAY enables the operator to initiate a data display routine.
EP	Indicator	When EP is illuminated, this informs the operator that present position must be entered. This indicator goes out when new position is entered.
ET	Indicator	When ET is illuminated, this informs the operator that the system has restarted, and present date and Greenwich time must be entered and the light goes out.
ACCEPT / INSERT	Switch-Indicator	The illuminated ACCEPT indicates that the operator should confirm the previously inserted data which is now displayed and press ACCEPT if the data is correct. The illuminated INSERT enables the operator to initiate data insert routines.

TABLE 3.2-9 OMEGA CONTROL-INDICATOR OPERATING CONTROLS AND INDICATORS (Continued)

Panel Marking	Type of Device	Function
SHIP N POS	Switch-Indicator	The illuminated SHIP enables the operator to enter data associated with the submarine or verifies that the data displayed is associated with the submarine. The illuminated N enables the operator to select the Northern hemisphere. The illuminated POS enables the operator to enter the new position of the craft or destination points or display the present position of the craft or destination points.
I A STATUS	Switch-Indicator	The illuminated 1 enables the operator to enter the numeric data 1 or select 10-1/5 KHz data or select that specific destination point. The illuminated A enables the operator to select data associated with OMEGA Station A or accuracy of the new craft positional data. The illuminated STATUS initiates entry into the following information display modes. The operator to examine the percentage of synchronization obtained in the "sync" mode. When not in the sync mode, it enables the operator to examine the signal strength of the three frequencies of each station. The display of predicted coherency information. The display of system failure information obtained as a result of testing BITE.
2 B VAR	Switch-Indicator	The illuminated 2 enables the operator to enter the numeric data 2 or select 13-3/5 KHz data or select that specific destination point. The illuminated B enables the operator to select data associated with OMEGA station B or accuracy of the new craft positional data. The illuminated VAR enables the operator to display positional variance. The value is used to determine the accuracy of the navigational data.

TABLE 3.2-9 OMEGA CONTROL-INDICATOR OPERATING CONTROLS AND INDICATORS (Continued)

Panel Marking	Type of Device	Function
3 | C / NCTR	Switch-Indicator	The illuminated 3 enables the operator to enter the numeric data 3 or select 11-1/3 KHz data or select that specific destination point. The illuminated C enables the operator to select data associated with Omega Station C. The illuminated NCTR enables the operator to display the number of Tracking Filter dumps to the Combinational Filter for each station.
4 | D / CSE/ETE	Switch-Indicator	The illuminated 4 enables the operator to enter the numeric data 4 or indicates that specific destination point. The illuminated D enables the operator to select data associated with OMEGA Station D. The illuminated CSE/ETE enables the operator to display the computer estimated time and Great Circle Course (true) based on current velocity from craft position to the selected destination.
5 | E / DT/GMT	Switch-Indicator	The illuminated 5 enables the operator to enter the numeric data 5 or indicates that specific destination point. The illuminated E enables the operator to select data associated with OMEGA Station E. The illuminated D/GMT enables the operator to insert date and Greenwich Time for use in OMEGA propagation predictions or display current date and time.
6 | F / LOP	Switch-Indicator	The illuminated 6 enables the operator to enter the numeric data or indicates that specific destination point. The illuminated F enables the operator to select data associated with OMEGA station F. The illuminated LOP enables the operator to display 2 OMEGA lines of position without propagation corrections.

TABLE 3.2-9 OMEGA CONTROL-INDICATOR OPERATING CONTROLS AND INDICATORS (Continued)

Panel Marking	Type of Device	Function
7 G / CAL H/S	Switch-Indicator	The illuminated 7 enables the operator to enter the numeric data 7 or indicates that specific destination point. The illuminated G enables the operator to select data associated with OMEGA Station G. The illuminated CAL H/S enables the operator to display the calculated OMEGA speed and track angle.
8 H / MAN H/S	Switch-Indicator	The illuminated 8 enables the operator to enter the numeric data 8 or indicates that specific destination point. The illuminated H enables the operator to select data associated with OMEGA Station H. The illuminated MAN-H/S enables the operator to insert speed and heading data or display manually inserted speed and heading.
9 MAN / AUTO H/S	Switch-Indicator	The illuminated 9 enables the operator to enter the numeric data 9 or indicates that specific destination point. The illuminated MAN enables the operator to allow or disallow use of manually inserted speed and heading data or verify that the manual is being allowed or disallowed. The illuminated AUTO H/S enables the operator to display the ship's EM log speed and Mark 19 heading inputs when in the AUTO input Reference Mode.
Ø S / INPUTS	Switch-Indicator	The illuminated 0 enables the operator to enter the numeric data 0 or select that specific destination point. The illuminated S enables the operator to select the Southern hemisphere.

TABLE 3.2-9 OMEGA CONTROL-INDICATOR OPERATING CONTROLS AND INDICATORS (Continued)

Panel Marking	Type of Device	Function
		The illuminated INPUTS enables the operator to insert the new reference mode of operation and stations or display the reference mode of operation and Omega stations that are allowed.
AUTO W BRG/RNG	Switch-Indicator	The illuminated AUTO enables the operator to allow or disallow the ship's EM log velocity and Mark 19 heading inputs as OMEGA reference data or verify that the ship's inputs are allowed or disallowed. The illuminated W enables the operator to select the Western Hemisphere. The illuminated BRG/RNG enables the operator to select the computed distance and Great Circle Bearing from the submarine, destination, or rendezvous point to another destination or rendezvous point for display.
RZ E COH	Switch-Indicator	The illuminated RZ enables the operator to select the moving destination as selected destination or verify that data displayed is associated with the moving destination. The illuminated E enables the operator to select the Eastern hemisphere. The illuminated COH enables the operator to select coherency values for each of the three frequencies for display. These values are the fractional part of the received phase information after corrections for the propagation. The non-base station displays are measurements with respect to the base station.

TABLE 3.2-9 OMEGA CONTROL-INDICATOR OPERATING CONTROLS AND INDICATORS (Continued)

Panel Marking	Type of Device	Function
COH	Switch- Indicator	The values are related to the present position. The phasing of the antenna can be checked by using this display. The base station display is the drift rate of the oscillator (T_o). COH when operated after STATUS provides a display of predicted phase measurement based on the systems calculated position and time which may be then compared to the actual measured phase contained in the tracking filters.

3.2.4.2.3* Omega Interface Box (See Figure 3.2-12) - Table 3.2-11 lists the functions of each control and indicator on the Omega Interface Box.

TABLE 3.2-11

Panel Marking	Type of Device	Function
CONT-IND PWR	Toggle Switch & Circuit breaker	Switches 115VAC, 400Hz to Control Indicator Panel; also will open circuits under abnormal load.
REC-COMP	Toggle Switch & Circuit breaker	Switches 115VAC, 400Hz to Receiver/Computer and also will open circuit under abnormal load.
REC-COMP HTR PWR, SYNCHRO SWITCH	Toggle Switch & Circuit breaker	Switches 115VAC, 400Hz to 28VDC Power Supply within Interface Box which in turn supplies 28VDC to oscillator heater in Receiver/Computer; also will open circuit under abnormal load.
REC-COMP HTR PWR	Indicator Light	Indicates 28VDC power supply is energized when on.
OSC HTR CURRENT	Push-Button Switch	When actuated, current supplied to oscillator heater can be measured with ammeter connected to TP 7 & TP8.
SYNCHRO TP1, TP2	Test Points	115 VAC, 400 Hz (R_1 & R_2) Speed Synchro excitation.
SYNCHRO TP3, TP4	Test points	115VAC, 400Hz (R, & R_2) Heading Synchro excitation.
SYNCHRO TP6, TP5	Test points	Heading excitation reference (26VAC, 400Hz)
SYNCHRO TP7, TP5	Test points	Speed excitation reference (26VAC, 400Hz)
TP8, TP9	Test points	Ammeter connections for measurement of oscillator heater current.
TP10, TP13	Test points	115VAC, 400Hz Control Indicator excitation.
TP11, TP13	Test points	115VAC, 400Hz Rec-Comp excitation
TP12, TP13	Test points	115VAC, 400Hz 28VDC Power supply excitation.

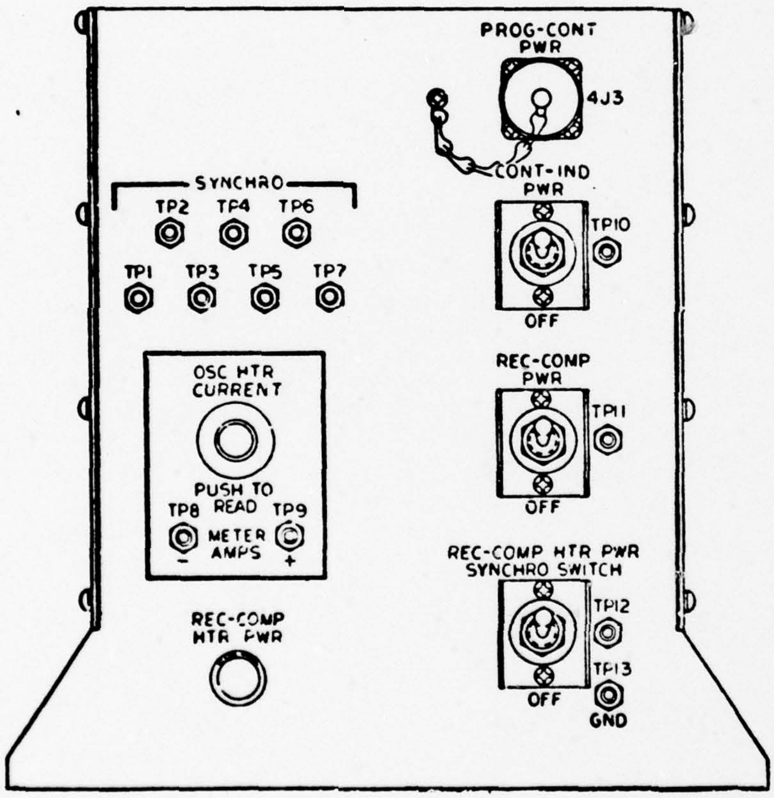


FIGURE 3.2-12 OMEGA INTERFACE BOX

3.2.4.3 Detailed Operating Procedures

3.2.4.3.1 Turn-On Procedure.

a) CABLE HOOKUP - Confirm that all cables are connected and Control Indicator power switch is off.

b) 400 CYCLE POWER - Verify that REC-COMP PWR and CONT-IND PWR circuit breakers on the Interface Box are on.

c) +28VDC POWER - Verify that REC-COMP HTR PWR, SYNCHRO SWITCH circuit breaker on the Interface Box is on and that REC-COMP HTR PWR indicator is on.

d) WARMUP MODE - Wait five (5) minutes for the oscillator oven to warm up.

e) OPERATE - Momentarily depress the POWER switch on the Control-Indicator panel; confirm that the indicators on the front of the computer (PWR MALF and BITE) do not come on; also confirm that the Control Indicator SYSTEM MALF light does not turn on. The SYSTEM MALF indicator will come on if OMEGA synchro excitation input from the ship's 115V 400 Hz heading reference gear train is turned off.

f) SYNC MODE - Confirm that the SYNC and ET lights come on 20 seconds after turn-on. (In the SYNC mode, the OMEGA system is determining the time reference of the OMEGA transmitting stations.) The SYNC light normally goes out within one minute after coming on if the normal VLF OMEGA signals are available.

g) ANTENNA SELECTION - Confirm that the ship's CU-1441 multicoupler is in the correct mode (See Omega CU-1441 Operating Procedure) and the correct antenna is selected. (LOOP-FLOAT indicator on Control-Indicator indicates which are being used.)

h) HEADING AND SPEED REFERENCE - The omega system requires ship's speed information for Omega phase rate aiding and dead reckoning calculations. It requires ship's heading to resolve the reference speed inputs into the north and east components and also for antenna loop selection. Select the ship's heading and speed inputs as follows:

- Press INSERT
- Press INPUTS
- Deselect either MAN or AUTO where the following inputs are used:

MAN H/S - Manual heading and speed

AUTO H/S - Mark 19 heading input and EM Log speed input

3.2.4.3.1 Turn-On Procedure (Continued)

- Confirm that the proper lamps stay on and the others off; also, that ACCEPT lamp comes on.

- Press ACCEPT and observe that the ACCEPT lamp goes off.

i) INSERT MANUAL HEADING AND SPEED - If the manual inputs are selected, insert the ship's speed and heading as follows:

- Press INSERT.

- Press MAN H/S.

- Press following numeric data.

(XXX°) (degrees)	(XX.X) (knots)
Heading	Speed

- Confirm numeric display and that the ACCEPT lamp is on.

- Press ACCEPT and observe that ACCEPT goes off.

j) DISPLAY SHIP'S HEADING AND SPEED REFERENCE - The EM Log speed input or Mark 19 heading input may be confirmed as follows:

- Press DISPLAY

- Press AUTO H/S

- Observe the following data:

(XXX°) (Degrees)	(XX.X) (knots)
Heading	Speed

k) DISPLAY OMEGA STATIONS ALLOWED - Confirm that the proper Omega transmitting stations are allowed and that the correct speed and heading reference mode has been selected as follows:

- Press DISPLAY

- Press INPUTS

- Confirm stations allowed (illuminated) and disallowed (dark) and the input reference mode. The number illuminated adjacent to the Omega station indicates that the station is the base station.

3.2.4.3.1 Turn-On Procedure (Continued)

NOTE

If a change in Omega stations allowed or disallowed is required (see 3.2.4.3.2,b), perform the following:

- Press INSERT
- Press INPUTS
- Press the station that is to be disallowed and observe that that particular light goes off.
- Press ACCEPT and observe that ACCEPT goes off.

l) INSERT DATE AND TIME - Insert the Date and Greenwich Meridian Time as follows:

- Press INSERT
- Press DT/GMT
- Press following numeric data:

(XX)	(XX)	(XX)	(XX)	(XX)	(XX)	
Yr.	mo.	day	hr.	min.	sec.	(Zulu Time)

- Confirm numeric display data and that the ACCEPT lamp is on.
- Press ACCEPT and observe that ACCEPT lamp goes off.

m) INSERT SHIP'S PRESENT POSITION - Insert the ship's present position as follows:

- Press INSERT
- Press POS
- Press SHIP
- Press following numeric data:

N/S	(XX)	(XX.X)	E/W	(XXX)	(XX.X)
	deg.	min.		deg.	min.
Latitude			Longitude		

- Press either A, B or C depending on the accuracy of the present position reference information where:

3.2.4.3.1 Turn-On Procedure (Continued)

A= .5 N.M. Max

B= 5 N.M. Max

C= 35 N.M. Max

- Confirm numeric display data and that the ACCEPT lamp is on.

- Press ACCEPT and observe that the ACCEPT lamp goes off.

n) AUTOMATIC MODE PROGRESSION - The SYNC lamp will go off within one minute after the Omega signals are available. The OMEGA system will then go into the frequency differencing mode to resolve lane counts and accurate navigational data will be available within five (5) minutes after the SYNC lamp goes off. If a B or C positional fix was originally inserted, the position uncertainty (POS UNC) lamp will come on during initial lane resolution.

o) DISPLAY OMEGA CALCULATED SPEED AND TRACK ANGLE - If the submarine is underway its Omega calculated speed and track angle being made good may be observed as follows:

- Press DISPLAY

- Press CAL H/S

- Observe the following data:

(XXX°) (degrees)	(XX.X) (knots)
Heading	Speed

3.2.4.3.2 Navigation Procedure

NOTE

The Omega System has been designed to automatically provide accurate navigational information with a minimum amount of manual operations and operator decision-making requirements. However, some decisions must be made by the operator.

a) POSITION FIX - There are times when the Omega system will acquire an excessive error requiring the operator to correct the Omega positional data. The positional error may be the result of a long period of time in the dead reckoning mode (no incoming Omega signals available) or erroneous Omega signals. The criteria for determining the largest possible position error from which the Omega system will recover is based on which stations are being received.

3.2.4.3.2 Navigation Procedure (Continued)

At least three Omega stations must be received to calculate positional information from Omega signals. To resolve position from the widest lane (72 N.M.) all three frequencies are required. For example, if Norway (Station A) is only transmitting two frequencies, the following maximum error can be resolved:

Two Stations and Norway	B Fix (5 N.M. Max.)
Three Stations other than Norway	C Fix (35 N.N. Max.)

b) STATIONS ALLOWED - Navigational accuracy can sometimes be improved by disallowing a station. If the AMB or POS UNC lights come on and/or Omega positional data is inaccurate, one station can be disallowed. (Remember that at least three stations are required to calculate Omega positional data.) The bad station can usually be identified by a low signal-to-noise ratio and/or high variance numbers on at least one frequency. If the ship is within 600 N.M. of a transmitting station, there is a possibility of strong incoherent signals being received. The present program automatically disallows station within 360 N.M.

NOTE

This can be detected by observing the N Counts which will stop counting. The station light will remain on unless the operator has manually disallowed it.

c) SHIP'S HEADING (USING FLOATER ANTENNA ONLY) - Since the floater antenna is directional, the ship's heading will have an effect on obtaining Omega navigational data. To obtain the best ship's headings, insert the Omega Station locations (Station A) Norway: 66°N, 13°E; (Station B) Trinidad: 11°N, 62°W; (Station C) Hawaii: 21°N, 158°W; (Station D) North Dakota: 46°N, 98°W; Japan: 35°N, 129°E in the "Destination" locations and obtain their bearings. A ship's heading which is close to right angles to a transmitting station will cause the loss of signals from that station.

d) NAVIGATION PERFORMANCE - The navigational accuracy of the Omega system can be evaluated on the following criteria:

- Displayed position data jumping around excessively, implies that navigational solutions have large variance.

- Ambiguity lamp (AMB) illuminated informing the operator that more than one state vector exists in positional solution calculation. Normally this implies that signals from one station are in error or the system is receiving insufficient information to completely define its present position.

3.2.4.3.2 Navigating Procedure (Continued)

- Position uncertainty lamp (POS UNC) illuminated which informs the operator that the program has gone into the difference frequency mode to resolve lanes. The system can be in error by as much as 30 N.M. when this light is on.

- A low signal-to-noise ratio on frequencies of stations implies that signals from that particular station are weak.

- High variances on a frequency of a station and very few Kalman dumps implies that the navigational solution is not using that particular input data.

- The positional variance (VAR) display will inform the operator of the accuracy of the OMEGA navigational data. When the value has reduced to below 0.4 n. miles it indicates that the position displayed is based upon sufficient Omega data to be accurate. It will in general reduce to 0.2 n. miles for strong signals from at least 3 stations. Its value upon insertion of a position fix will display the value associated with the type of fix.

e) MISCELLANEOUS NAVIGATIONAL AIDS - The Omega system can calculate and display the Bearing, Range, Estimated time to at present speed and Great Circle Course to, any one of ten fixed destinations and one moving destination (rendezvous). The Bearing and Range between any two of the destinations can also be calculated and displayed.

o INSERT DESTINATIONS - Insert destination position as follows:

  - Press INSERT

  - Press POS

  - Press 0 or 1, ..., or 9 to select destination number.

  - Press Numeric data as follows:

N/S	XX°	XX.X	E/W	XXX°XX.X
	deg.	min.		deg. min.
	Lat			Long

o INSERT MOVING DESTINATION POSITION - Insert moving destination position position as follows:

  - Press INSERT

  - Press POS

  - Press RZ

3.2.4.3.2 Navigating Procedure (Continued)

- Press Numeric data as follows:

N/A	XX°XX.X	E/W	XXX°XX.X
	deg.min		deg.min
	Lat.		Long.

- Confirm data on numeric display and that ACCEPT lamp is illuminated.
- Press ACCEPT and confirm that ACCEPT lamp goes off.

o INSERT MOVING DESTINATION HEADING AND SPEED - Insert moving destination speed and heading as follows:

- Press INSERT
- Press MAN H/S
- Press RZ
- Press Numeric data as follows:

XXX°	XX.X
Heading	Knots

- Confirm data on numeric display and that ACCEPT lamp is illuminated.
- Press ACCEPT and confirm that ACCEPT lamp goes out.

o DISPLAY PRESENT POSITION OF SUBMARINE, DESTINATION, OR RENDEZVOUS POINT - Display the position of a submarine, destination, or rendezvous point based on the ship's present speed and heading as follows:

- Press DISPLAY
- Press POS
- Press SHIP, p, 1, . . . or 9 or RZ to select the destination
- Observe the data on the display.

NS	XX°XX.X	E/W	XXX°XX.X
	deg.min.		deg.min.
	Lat.		Long.

o DISPLAY BEARING AND RANGE BETWEEN ANY TWO OF THE FOLLOWING POSITIONS: SUBMARINE, DESTINATIONS, AND POINT OF INTERCEPT - Display the range and bearing between the submarine, the destinations, and the point of

3.2.4.3.2 Navigating Procedure (Continued)

intercept of the moving destination as follows:

- Press DISPLAY
- Press BRG/RNG
- Press SHIP or 0 or 1 ... or 9 or RZ (From)
- Observe the data on display.

XXX°	XXXX.X
Bearing	Range

o DISPLAY COURSE AND ESTIMATED TIME ENROUTE - Display the estimated time to destination or rendezvous point and course. (True Great Circle Path) at the ship's present speed as follows:

- Press DISPLAY
- Press CSE/ETE
- Press 0, or 1 ... or 9 or RZ to select destination
- Observe the data on display.

XXX°	XXX.X
Deg.	Hrs.

o LOP DISPLAY - Since surface ships use an Omega receiver which displays uncorrected lines of position (LOP), they may request the submarine's LOP to seek a relative position to them for rendevous purposes. Display two sets of LOP's as follows:

- Press DISPLAY
- Press LOP
- Press (A,B), (A,C), (A,D), (B,C), (B,D) etc, to select a pair of stations defining one LOP.
- Repeat above for the second set of LOP's.
- Press either 1, 2 or 3 to select the frequency where 1 = 10 1/5 KHz 2 = 13 3/5 KHz and 3 = 11 1/3 KHz.
- Confirm the frequency and station pairs that are displayed.

3.2.4.3.2 Navigating Procedure (Continued)

- Observe the two sets of LOP's.

o DISPLAY FILTER DATA - To display the number of Kalman dumps, data counter, and Omega data variance:

- Press DISPLAY
- Press NCTR
- Press A thru H to select station (NOTE: This display will not contain useful data for the "Cnt" and "N" segments if that station has been deselected).
- Observe the display

10.1/5 KHz			13.3/5 KHz			11.1/3 KHz		
Cnt	N	V	Cnt	N	V	Cnt	N	V
XX	X	X	XX	X	X	XX	X	X

"Cnt" is the total number of times that tracking filter data has been used by the Kalman filter to update position. The maximum rate of updates is two (2) per minute and typically is one per minute. Update rates less than one per 5 minute period indicates very poor signal reception from this station. "N" is a counter which increments when the received burst measurement variance is acceptable and the tracking filter phase and phase rate variances are below a specific level. When this number reaches (3) or more, the tracking filter data is ready and waiting for use by the Kalman filter. "V" indicates the phase variance of the data in the tracking filter. When the Kalman filter accepts data from other than the base station tracking filter, both the phase and phase rate variances are reset to a high value. This is indicated by the "N" count going to "0" and the "V" value going to 9. The "N" counter will then start to count back up as soon as the tracking filter variances are below predetermined values. If subsequent burst measurements drive either variance above this value the "N" counter is again reset to zero. However, in this case the variances are not reset and the Kalman "Cnt" remains the same. The only difference between the base and non base station is that the base station tracking filter variances are not reset when used by the Kalman filter.

o DISPLAY SYNC STATUS AND SIGNAL STRENGTH DATA - During the interval of time that synchronization is being obtained with the Omega Transmitters and as identified by the illumination of the SYNC indicator, the progression of this process may be observed as follows:

- Press DISPLAY
- Press STATUS

3.2.4.3.2 Navigating Procedure (Continued)

- Press either 1, 2 or 3 to select the frequency where 1 - 10 1/5 KHz, 2 = 13 3/5 KHz, and 3 = 11 1/3 KHz.

- Observe the display

```
 XX    XX    XX         XX    XX    XX
Blank       Percent          Blank
             Sync
```

The most digits in the left display will show a number between 00 and 99 indicating a percent completion of the synchronization process. Once synchronization has been completed (SYNC light out) the display will automatically change to the following:

```
X X X X X X        X X X X X X
A B C D            E F G H
  Stations           Stations
```

Each digit can have a value anywhere between 0 to 9 dependent upon the signal to noise ratio of the Omega signal at the antenna input. The higher the number the greater the signal to noise ratio for that station on the selected frequency. The station being identified in the display by its usual letter symbol A thru H. This display is also very useful in ascertaining that the automatic synchronization has been performed correctly. This is done by observing that the higher signal to noise numbers correspond to the nearest transmitters.

o PREDICTED COHERENCY DISPLAY - To display coherency values for both predicted and tracking filter measured values:

- Press DISPLAY

- Press STATUS

- Press COH

- Press A thru H to select station

- Observe the display

3.2.4.3.2 Navigating Procedure (Contunued)

X X X X X X	X X X X X X
10-1/5 11-1/3 13-3/5	10-1/5 11-1/3 13-3/5
Predicted	Measured

The indicated "Measured" information is the actual phase measurement data taken from the output of the tracking filter for the propagation delay. This number should be compared to the "predicted" information for the same corresponding frequency. The predicted information is based on the system derived position which is the Omega chart value for station minus base. Each pair of numbers is in terms of percent of lane (cec's) and will vary from 00 to 99. This display can be used as an aid in determining that the loop antenna phasing is correct as described previously. It is also beneficial in determining whether the Omega signals being received from the transmitters are coherent. There are certain times of the day and geographical areas when this information has been observed to be shifted by a greater degree than should be expected and corrected by the propagation delay model. For example the Norway signals as received along the East Coast of the United States are very unpredictable and incoherent. Also at night when approaching a transmitter the signals may be incoherent at a distance greater than 360 miles which are automatically eliminated by the software program. By using this display and observing that the frequency corresponding "Measured" and Predicted coherency information agree to within about 10 CEC's, then those Omega transmitted signals should be used and should be allowed.

o SYSTEM MALFUNCTION DISPLAY - To display what system built-in-test (BIT) has failed:

- Press DISPLAY
- Press STATUS
- Press INPUT
- Observe the display

The following codes are used to identify the system malfuction:

INDICATOR	BIT Program
A	Rf Section test VLF 10.2 KHz
C	Rf Section test VLF 13.6 KHz

3.2.4.3.2 Navigating Procedure (Continued)

INDICATOR	BIT Program	
E	Rf Section Test	VLF 11 1/3 KHz
4	Rf Section Test	RCVR SF or Bias
5	Rf Section Test	RCVR SF or Bias
6	Rf Section Test	RCVR SF or Bias
B	Phase Angle/Digital Converter Test	10.2 KHz
D	Phase Angle/Digital Converter Test	13.6 KHz
F	Phase Angle/Digital Converter Test	11 1/3 KHz
0	Phase Counter I/O Test	UP
1	Phase Counter I/O Test	UP/DOWN
2	DMA I/O Test	
3	GP Test	
7	RF Pre Amp Test	
8	Excitation Test	Synchro A
9	" "	Synchro B
G	Computer A/D Converter Test	
S	Memory Checksum Test	
AUTO	Frequency Stability Test	

3.2.4.3.3 Shutdown Procedure

a) CONTROL AND DISPLAY PANEL - Actuate Control Indicator POWER switch momentarily to de-energize system.

b) 400 CYCLE POWER - Turn off circuit breakers at the Interface Box.

3.2.4.3.4 OMEGA/SHIP'S CU-1441/BRR Operating Procedures - The following switch positions will cause loss of Omega signals:

a) Power OFF.

b) Loop Control and Tuning Plug-In at TUNED.

c) Navigation Plug-In at BYPASS-Floater or LOOPs depending on mode.

3.2.4.3.4 OMEGA/SHIP"S CU-1441/BRR Operating Procedures (Continued)

d) Communications Plug-In at BYPASS LOOP.

e) Navigation Plug-In at wrong mode, FLOATER or LOOP.

NOTE

In the Loops Mode, the Navigation plug-in, Multicoupler switch must be at LOOPS position and the loop tuning control must be in the BROADBAND position. In the Floater Mode, the Navigation Plug-In must be at FLOATER position and the Floater plug-in must have power ON, Gain switch at HIGH position, and Impedance switch at 3 or 4.

If the CU-1441/BRR is not providing OMEGA signals, the signal status display will show the loss or high noise on all frequencies and stations. The SIG LOSS lamp will also be illuminated on the Control and Display Panel.

3.2.4.3.5 Power Drop-Outs

The system will automatically shut down and automatically come back on in the sync mode. The response is the same as if the operator shut down the system via the Control Indicator and then turned the system back on. The new time and position (if the dropout was longer than 5 minutes duration) must be inserted. The old Omega operating mode and reference selection mode will not change during a dropout.

If the power dropout was of short duration, the time and position may be correct but the ET lamp will be illuminated. This situation is cleared as follows:

- Press INSERT
- Press DT/GMT
- Confirm that the data and time are correct.
- Press the ACCEPT and observe that the ACCEPT and ET lamps go out and the EP lamp comes on.
- Press INSERT
- Press POS
- Press SHIP
- Confirm that the position data is correct and the ACCEPT lamp is illuminated.

3.2.4.3.5 Power Drop-Out (Continued)

- Press ACCEPT and observe that the ACCEPT and EP lamps go out.

3.2.5 Detailed System Operations

3.2.5.1 General

Since the unique feature of the Submarine OMEGA Navigation Set is its ability to provide rapid and accurate navigational data based on the computer software routines, this paragraph briefly describes the overall operation. The subsequent paragraphs will provide detailed description of the software routines performed by the computer to obtain the positional data.

The transmitted OMEGA signals received through the two orthogonal loop or floater antennae on the submarine are supplied to the OMEGA orthogonal loop antenna coupler via the ship's CU-1441/BRR Antenna Coupler Unit. The antenna coupler filters and amplifies the OMEGA signals and supplies the signals to the antenna switching matrix in the receiver-computer. The antenna switching matrix enables the computer to select an antenna configuration which will be best suited for the specific operation.

The OMEGA signals passed through the input gate circuit in the antenna switching matrix are phase shifted and summed, and then supplied to the receiver strips. Each receiver strip is tuned to a different OMEGA frequency. The receiver strip processes the OMEGA signal through amplifier and filter circuits in the RF and IF portions of the receiver. The output from the IF portion is supplied to the mixer in the correlator and digital converter.

The mixer processes the IF output with reference signals provided by the precision frequency generator to obtain sine and cosine phase information. This sine and cosine phase information is supplied to the analog-to-digital converter where the phase information is converted into digital form required by the computer. This digital information is supplied to an accumulator in the receiver-computer input/output circuit. When instructed by the computer, this information is supplied to the synchronization routine which aligns program timing to the real world.

After synchronization (Figure 3.2-13), the computer program allocates incoming signals to the OMEGA Processor (Figure 3.2-14), which computes the phase of each burst from the sine and cosine inputs, then calculates and removes erroneous phase shifts induced by phantoms, scale factor discrepancies and hardware. The OMEGA Processor also measures noise, and from this calculates the variance of the incoming signal which is an estimate of the signal validity. This first phase measurement calculation will be differenced with another phase measurement originating from a station which has been currently designated as the base station due to a higher signal strength. The resulting phase difference will be processed by the Tracking Filter routine, Figure 3.2-15, which will smooth the phase difference measurement and recalculate the validity estimate. When the value of the validity estimate passes an established criterion, the phase difference estimate is deemed usable by the Combinational (Kalman) Filter, Figure 3.2-17.

The Combinational Filter will further smooth the phase difference data with information derived from environmental conditions in the real world from the Propagation Prediction routine, Figure 3.2-16. From this the present position and velocity error corrections are derived and transmitted to the Navigation routine, which updates the existing latitude, longitude and velocity.

In the following paragraphs, the Synchronization, OMEGA Processor, Tracking Filter, Combinational Filter and Propagation Prediction routines are described. These five routines incorporate the majority of functional requirements defined in Section 3.3, and provide the reader with a general overview of the OMEGA Software.

3.2.5.2 Synchronization (See Figure 3.2-13.)

In order to measure the phase of the incoming OMEGA bursts, the software system in the OMEGA Navigation Set must align the transmitted OMEGA pattern with a known transmitted pattern. The two patterns must be aligned within 0.05 second. The method of synchronization is based on the fact that the 10-second period lacks symmetry. For example, a recorded 0.9-second burst must be followed by either a 1.0 or a 1.2-second burst. In either case, the total reception pattern can be identified.

It would appear that a data gathering period over a few seconds would produce at least two bursts which would then establish synchronization. However, the problem is that too often the signals are absent or buried in noise, so that an accurate time count of the burst length from any one station will be difficult. Therefore, the synchronization routine records a 10-second transmission period in increments of 0.1 second starting at some arbitrary time. In this way, the received 10-second pattern is partitioned into 100 distinct entities or slots. The first four of these 100 slots are shown in Figure 3.2-13. To then obtain synchronization, the slot numbers can be manipulated with the mathematical technique of differential correlation.

The mechanization is based upon the phase coherency of the bursts as opposed to the incoherent phase relationship of the 0.2 second period of non-transmission between bursts. A slot number representing a portion of a burst is composed of a succession of 20 digital outputs from each of the sine and cosine correlators. These are phase measurements, but they contain an unknown phase shift which has been introduced by the antenna. During synchronization, the orthogonal loop antenna is used in a pseudo omni-directional mode which shifts the incoming phase measurement an amount proportional to the station bearing which is unknown until synchronization has been completed. However, the incorrect measured phase is unimportant at this time since all that is required is a succession of sign-consistent numbers from the correlators to identify a burst. These are summed to obtain the slot value. On the other hand, a slot number which represents a portion of a period between

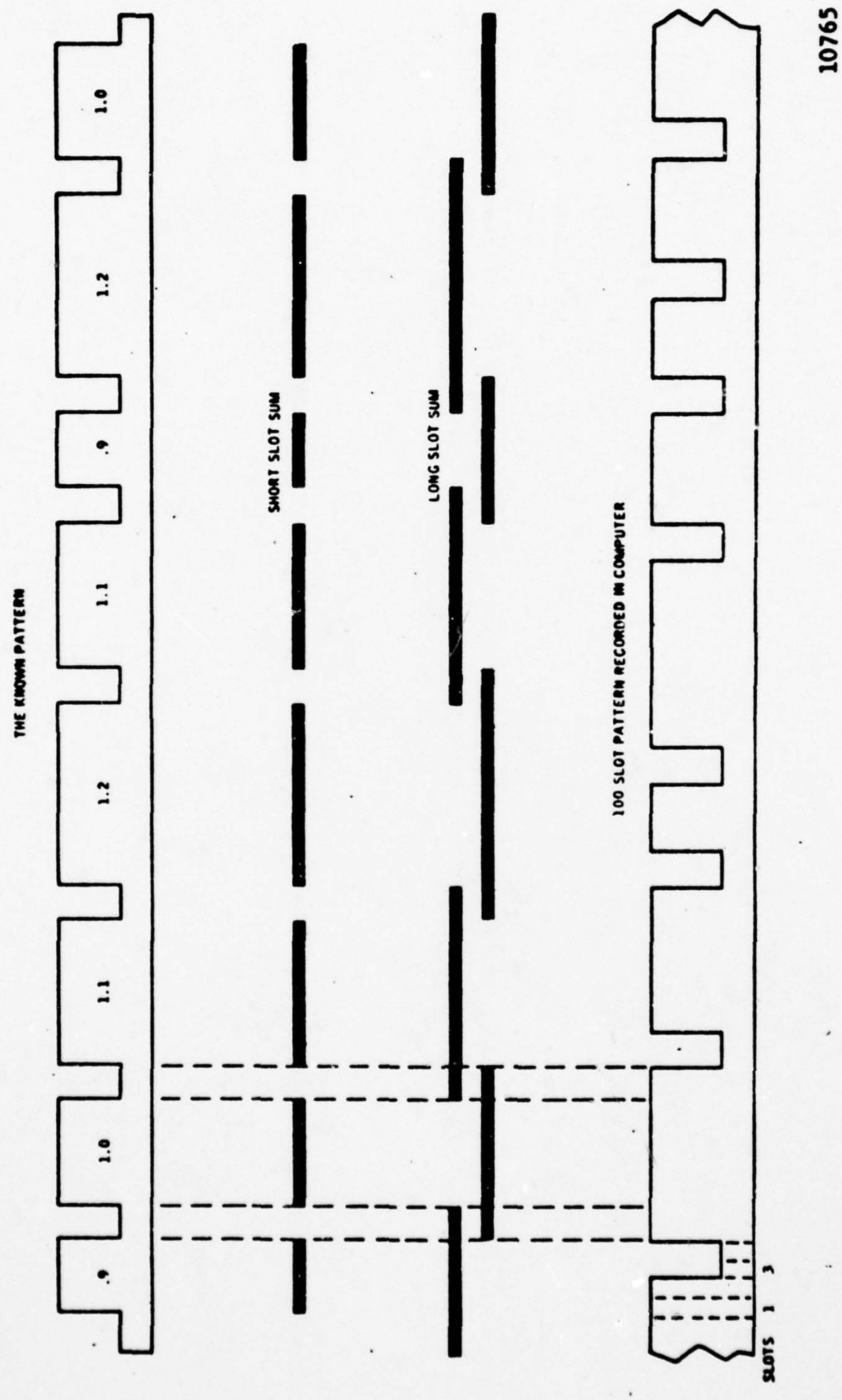


FIGURE 3.2-13 OMEGA SIGNAL SYNCHRONIZATION

bursts is made up of the correlator sine and cosine outputs whose values are random because of the phase incoherency of white noise, and whose sum should be close to zero. Thus, a slot number representing a burst is a non-zero number.

To match the transmitted burst to the known pattern, the synchronization routine uses the differential correlation technique which calculates the average squared value over a short-slot sum, over a long-slot sum, then takes the difference. The short and long-slot sum pattern is illustrated in Figure 3.2-13. After eight of these differences are obtained, they are summed and the resulting correlation number is associated with slot number 1. This process is repeated 100 times until the 100 possible start times in the 10-second period of station's transmission are exhausted. The 100 stored correlation values are then tested for the maximum.

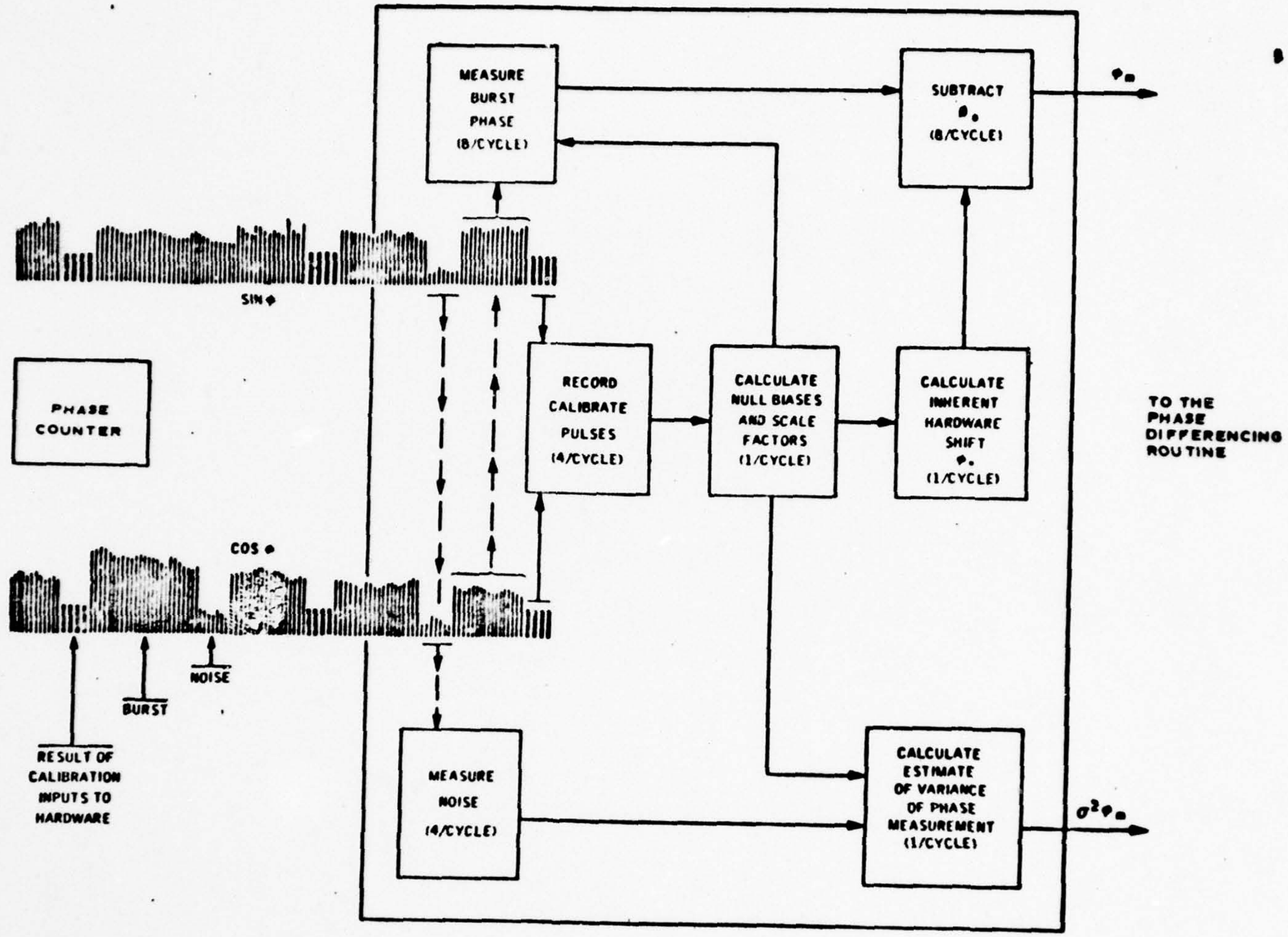
Confidence that synchronization is complete is based on comparing the extreme correlation value with the next best correlation value. When the best value exceeds the next best by a fixed amount, synchronization is complete. It is possible that the correlation test will not be satisfied by the values generated for the first 10-second period. Therefore, this process will be repeated for successive 10-second periods. This process will cycle through the three OMEGA frequencies using one of them in each of the 10-second periods. This will require that one set of 100 X's and 100 Y's be stored for future processing while the previous set is being used in the computation of the correlation values.

3.2.5.3 OMEGA Processing Routines (See Figure 3.2-14)

The primary function of the OMEGA Processor is to obtain the first measure of burst phase and its variance. It also controls the antenna switching matrix to obtain an antenna configuration best suited for a specific operation.

Once synchronization has been verified, the OMEGA Processor can assign meaning to the sequence of digital (sine and cosine) outputs from the correlators. However, the correlators use dual slope integrators which sometimes have a bias and which must be calibrated and filtered. To do this, a series of four test signals are injected, one at a time, into the receiver at every alternate period of non-transmission during a 10-second broadcast cycle. Using a known input, it is possible to calibrate the output (measurement) from the dual slope integrator. There is also a phase shift introduced by the receiver which must be subtracted from the burst phase measurement. The same calibration signals are recombined to yield this value.

Since there are eight non-transmission periods between bursts in a broadcast cycle, and four used for calibration signals, then this leaves four for measurement of noise, which also include spurious phantom signals which are internally generated. In this way, the signal-to-noise ratio is obtained



10766

FIGURE 3.2-14 OMEGA PROCESSING ROUTINE BLOCK DIAGRAM

yielding a measure of phase credibility which will be identified as the estimate of phase measurement variance and supplied, after phase differencing, to the tracking filter for further processing.

The antenna switching matrix is controlled by the OMEGA Processor. The antenna selection program uses the ship's heading, and the known station location, in the antenna selection routine to maximize the incoming burst signal-to-noise ratio. In effect, this increases the sensitivity of the orthogonal loop antenna to the incoming burst signal. This is accomplished by controlling the input gates in the antenna switching matrix to allow signals from loop A or loop B to enter the receiver strip.

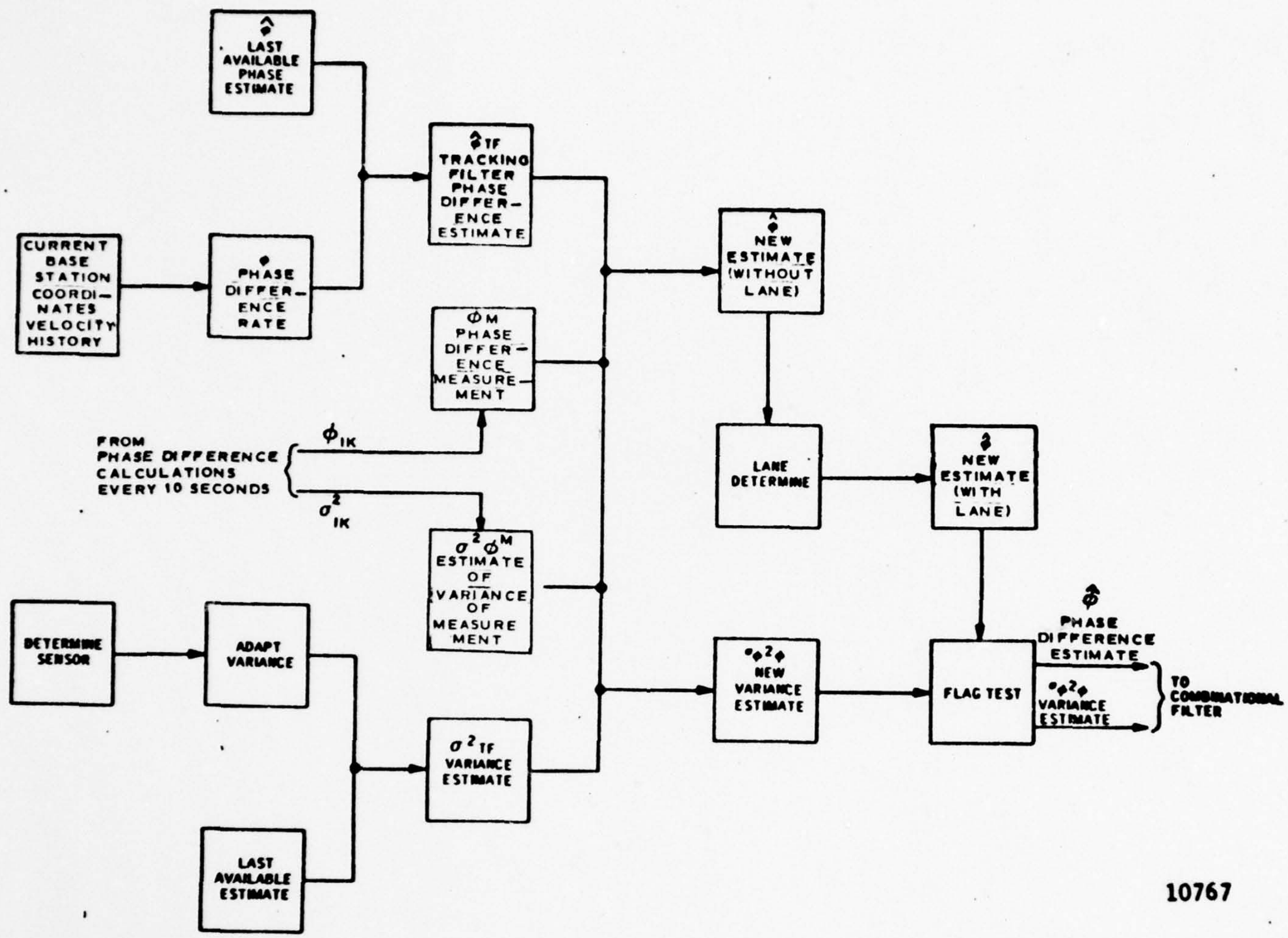
3.2.5.4 Tracking Filter (See Figure 3.2-15.)

There are 24 distinct adaptive, tracking filters provided in the system. One is provided for each of the three OMEGA frequencies and one for each of the eight OMEGA stations. Inputs to the tracking filters consist of measurement of phase difference and a computed variance of this measurement provided by the phase difference calculations. This measured phase difference is then compared with an estimated value of phase difference which the tracking filter computes based upon previous measurements to provide a new estimate of phase difference.

In order to compare average successive phase difference measurements spaced 10 seconds apart in time, it is convenient to remove the effect of the change in phase difference due to ship's speed. To accomplish this task, velocity information from an external source is sometimes provided for the tracking filters. The external sources providing velocity information are the Ship's E.M. Log or a manually inserted velocity and the Mark 19 heading reference or a manually inserted heading.

The velocity inputs to the tracking filter consist of the north and east components of velocity averaged over the previous time interval. The tracking filter then computes the component of velocity along the direction from the submarine to the transmitting station. This phase difference rate is then used to update the tracking filter phase difference estimate over the 10-second interval since the last measurement. In addition to estimating phase difference, the tracking filter also estimates phase difference rate error. This is the error in phase difference rate as computed from the velocity source. The estimated phase difference rate error is used to correct the computed phase difference rate in the time update of the phase difference stimate.

In addition to computing estimated phase difference and phase difference rate error, the tracking filter also computes the variance of error in estimating phase difference, the variance of the error in estimating phase difference rate error, and the cross variance. It is the computation of these variances along with the phase difference determined by the phase



10767

FIGURE 3.2-15 TRACKING FILTER ROUTINE BLOCK DIAGRAM

difference calculations that allows the tracking filter to statistically average this output with the new estimated phase difference at the tracking filter to obtain a single phase difference measurement and a single confidence number. Whether this averaged phase difference measurement is acceptable or not depends on the confidence number. That is, if the variance (confidence) is less than a specified number, the tracking filter "throws up a flag" which informs the combinational filter that new data is ready for processing. If the variance is too large, the tracking filter will not "throw up a flag" and the combinational filter will bypass tracking filter output in the next iteration. The tracking filter will continue this averaging until the variance is low enough to pass the "flag test".

3.2.5.5 Propagation Prediction Routine (See Figure 3.2-16.)

The output from the propagation prediction routine is an input to the combinational filter. Thus far, the computer has concentrated on determining a precise phase estimate of the incoming bursts. Knowing this phase and the locations of the eight stations, we can establish our exact location. However, phase velocity must be calculated and supplied to the combinational filter to obtain an accurate position data. The spherical earth correction, phase velocity correction, and radius correction must be calculated and supplied to the combinational filter. The phase velocity is calculated by determining where the broadcast stations are located with respect to the OMEGA receiver, where the sun is located with respect to the great circle paths between the receiver and the stations, the classification of earth surfaces under those paths, the path angle of the intersection to the earth's magnetic field, and the magnetic field latitude of the receiver.

3.2.5.6 Combinational Filter (See Figure 3.2-17.)

Inputs to the combinational filter are provided by the tracking filters and the propagation prediction circuit. The combinational filter provides a means of computing optimal estimates of position and velocity along with other elements of its state vector. The filter also performs the coordinate conversion from phase to geodetic coordinates (latitude and longitude) and lane determinations.

The combinational filter utilizes two types of observations. One is the difference between the phase difference of the tracking filter and a value of phase difference based upon the combinational filter's updated position. The other consists of a received correction to position entered through the OMEGA control-indicator panel. Based on these measurements, the combinational filter computes optimal estimates of: position errors, driving velocity errors, and oscillator drift.

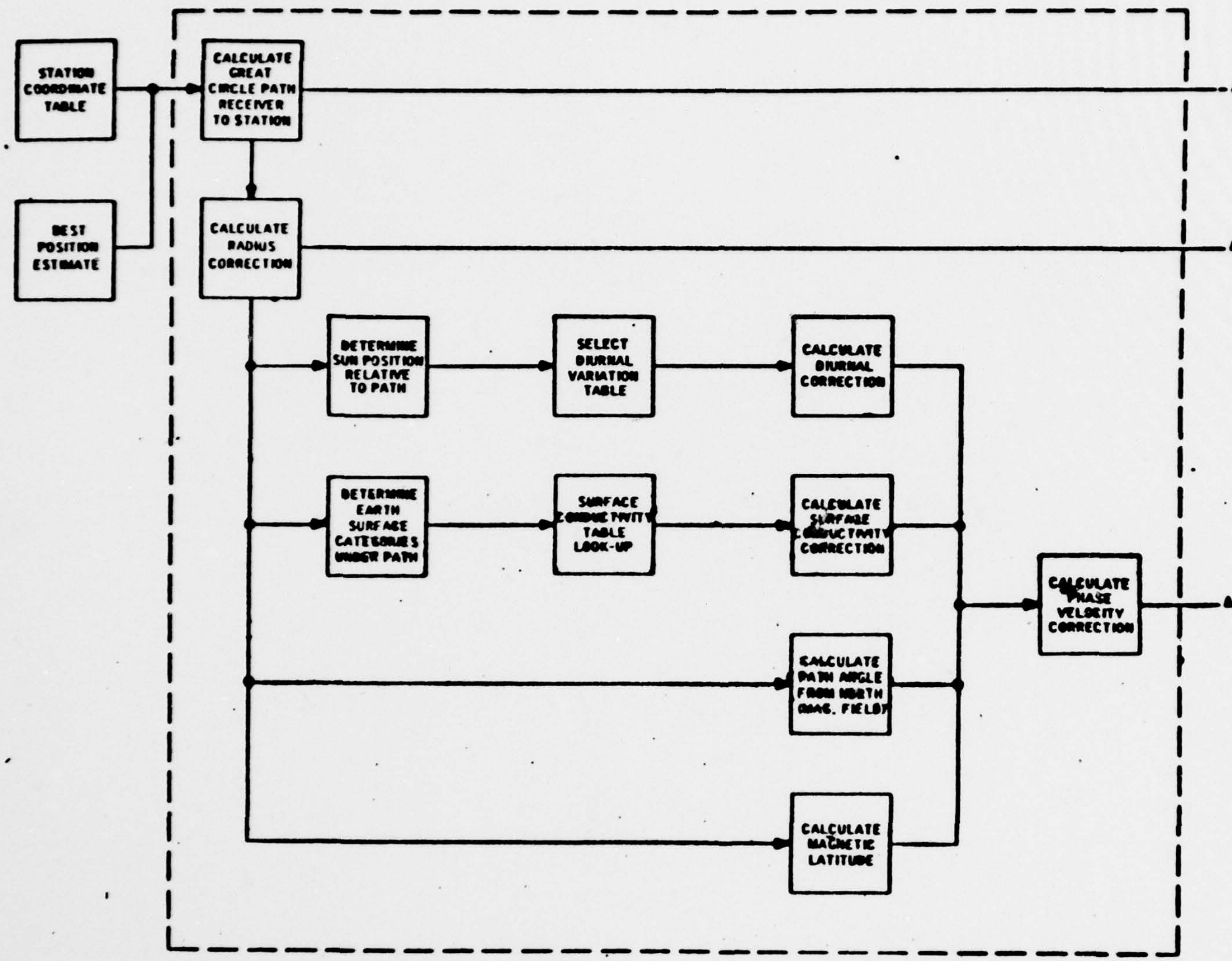
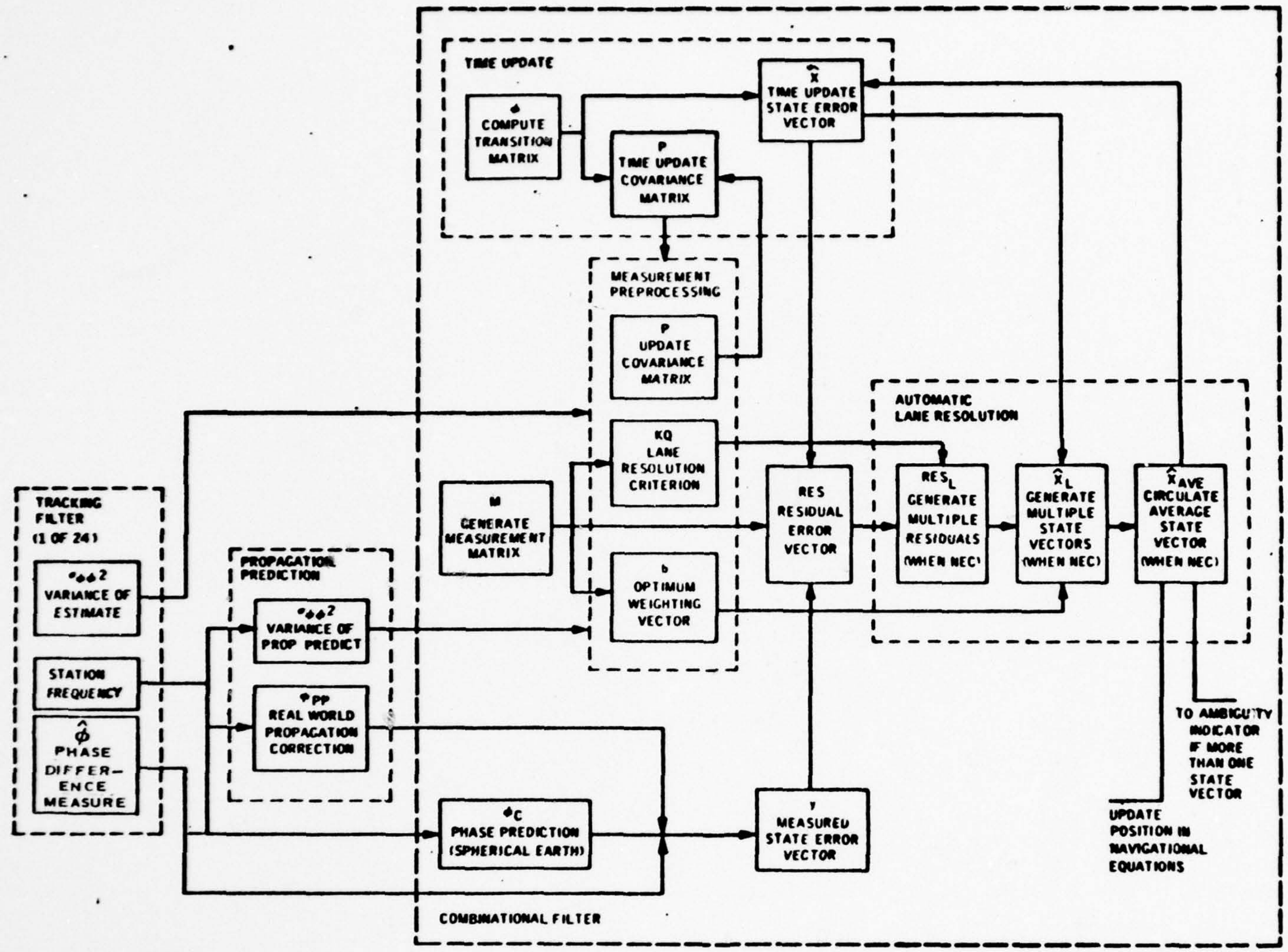


FIGURE 3.2-16 PROPAGATION PREDICTION ROUTINE BLOCK DIAGRAM



10769

FIGURE 3.2-17 COMBINATIONAL FILTER ROUTINE BLOCK DIAGRAM

Once the system errors are determined, the combinational filter updates its estimates of all system errors. In addition to the estimate of system "goodness", the covariance matrix is updated to reflect the inclusion of this new information. The estimates that result from using multiple frequencies are then combined to remove the ambiguity arising from the multiple OMEGA lanes.

The combinational filter also predicts, in its time update, how the system errors will increase as a function of time and how the "goodness" is then used to determine the optimum weighting when subsequent measurements are made. The recursive character of the filter allows long data strings of past measurements to be combined into a few parameters; thus, the entire system operation resides with the last estimate. This optimal estimate of the state of the system is called the state vector.

3.3 DETAILED FUNCTIONAL REQUIREMENTS

3.3.1 Synchronization

3.3.1.1 Introduction

a) In order to utilize the OMEGA signals for position determination, it is necessary to identify which stations are being received at all times. Measurements of phase must be solely that of particular stations and not contaminated by phase measures made when the station is not broadcasting, and certainly not when contaminated with the phase of other stations. In other words, the computer's computational cycle must be brought into alignment, or synchronized, with the station's broadcast cycle to within 0.05 second.

b) The station's transmissions are time multiplexed and synchronized to each other. The duration of each transmission follows a prescribed schedule so that a particular transmission pattern for the entire OMEGA network is produced. The transmission schedule for the 10.2 kHz frequency is shown below.

Station	Transmission Time (Sec)
A	0.9
B	1.0
C	1.1
D	1.2
E	1.1
F	0.9
G	1.2
H	1.0

c) There is a nominal gap of 0.2 second between transmission to account for propagation delays from transmitter to receiver. Thus the pattern of signal envelope for the entire station network could have the appearance as shown in Figure 3.3-1 (no noise and equal amplitudes such as produced by a high gain receiver with limiting). The cycle repeats every 10 seconds for each of the three OMEGA frequencies.

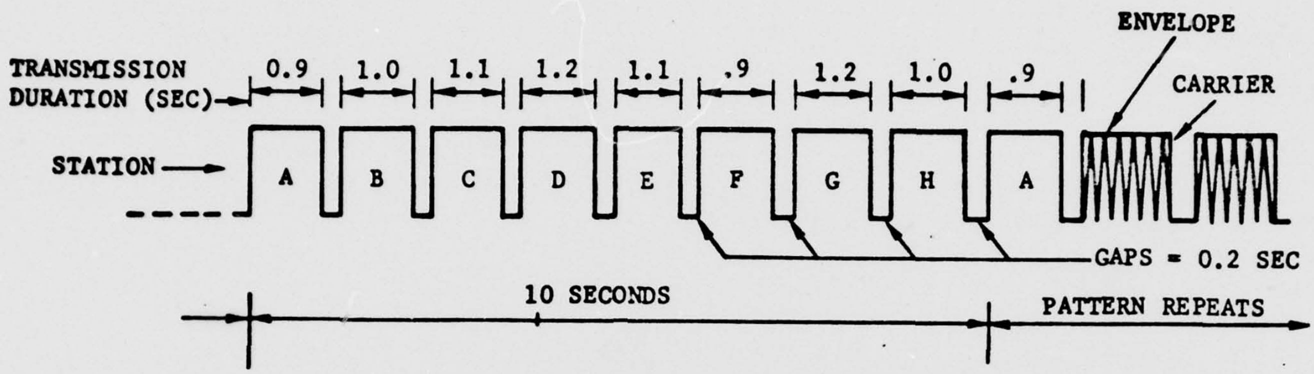


FIGURE 3.3-1 OMEGA TRANSMISSION ENVELOPE

d) As can be seen in Figure 3.3-2 the scheduled length of each station's transmission produces a unique code which can be used to detect the transmission pattern. Relative to a unit transmission length of 0.9 second, the cross-hatched area gives the excess energy associated with each station's transmission. The computer, in essence, creates a corresponding pattern starting at an arbitrary time.

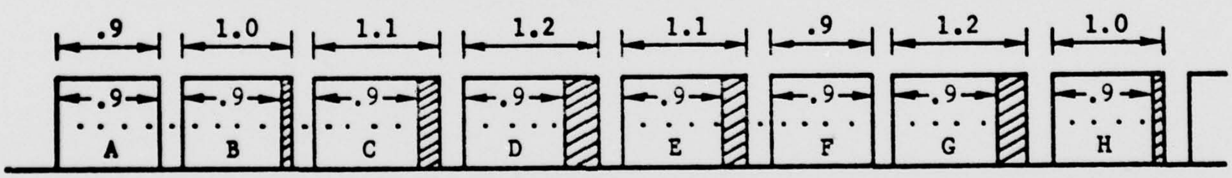


FIGURE 3.3-2 THE DISSYMMETRY OF THE PATTERN

e) The correlation between the computer's pattern and the incoming signal pattern is then computed based on an arbitrary computer start time, t*. The correlation value and its corresponding start time is stored.

3.3.1.2 Inputs

a) Input Format: The signals supplied to the computer are in the form of sine and cosine of signal phase relative to the local clock:

$$X = \overline{\sin \phi}$$

$$Y = \overline{\cos \phi}$$

These quantities averaged in the hardware

Φ is the phase angle. X and Y are the computer inputs. The bar over sin Φ and cos Φ represents the averaging process which takes place in the encoding section of each receiver. Since (X, Y) samples are transferred into the computer 200 times per second, the bar represents averaging over 5 ms. These X, Y samples are accumulated in two computer memory cells (for each receiver strip), X_{ACC}, Y_{ACC}, and 20 such samples are accumulated, i.e.,

$$X_K = \sum_{j=1}^{20} X_j$$

$$Y_K = \sum_{j=1}^{20} Y_j$$

corresponding to 0.1 second of real time. 100 such samples of both X_K and Y_K are developed and saved in a 10-second interval.

b) Input List:

Input	Units	Range	Resolution	From
X	Counts	0 → ±20	1	I/O
Y	Counts	0 → ±20	1	I/O
STAT MRK_i i=A,B,...H	Marker	---	---	I/O

3.3.1.3 Processing

The initial task of the synchronization function is to set SYNC MRK = true. This marker will illuminate the SYNC indicator on the Control-Indicator panel to inform the operator that synchronization is in progress.

Synchronization computations will be made using data from one frequency at a time. The computer program will establish an arbitrary start time and input a block of data corresponding to a 10-second interval. This data will be correlated with the expected pattern in an attempt to establish synchronization. If not successful, another 10-second block of data is inputted, using the next frequency. Beginning with 10.2 kHz synchronization is sequentially attempted on 10.2, 13.6, 11-1/3, 10.2 etc., until successful, or until the operator intervenes.

Synchronization will be established using a differential correlation technique. The 10-second data input will be stored as 100 sine sums and 100 cosine sums, representing contiguous 100 ms intervals for the frequency under consideration.

These 100 sums are formed as follows, from the input data;

$$X_K = \sum_{j=1}^{20} X_j \qquad\qquad Y_K = \sum_{j=1}^{20} Y_j$$

K=1,100 K=1,100

where X_j and Y_j are the inputs receivered every 5 ms from the receiver, each representing an average over 5 ms.

By first assuming that burst number one (Station A on 10.2 kHz) starts with the first 100 ms interval of data stored in the computer, a correlation number, C1 can be established as a "measure of fit". This can then be compared with the correlation numbers C_2, C_3, ..., C_{100} found by assuming in turn that burst number one starts with the second, third, ..., and 100th interval, respectively. For purpose of notation in subsequent equations, it is assumed the correlation numbers are referenced with an Index I, ranging 1 to 100.

To form the correlation numbers, the computer program will determine a long sum over the group of 100 ms intervals assumed to comprise burst number one plus the data in the slots on either end of it. The long sum is differenced with a short sum computed over the burst alone. Figure 3.3-3 illustrates the intervals of data spanned by the two computations. The long sum and short sum are determined by the following equations.

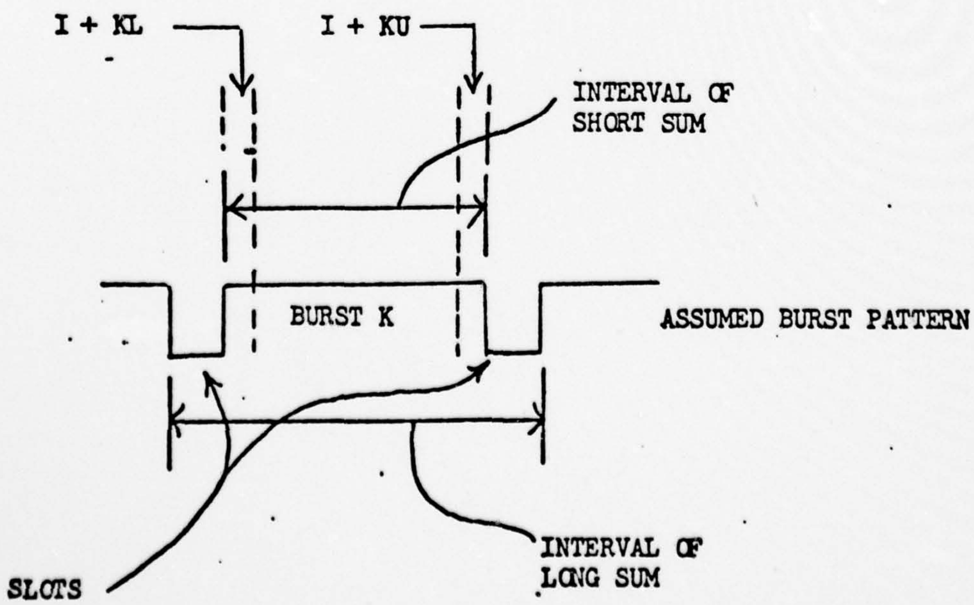


FIGURE 3.3-3 LONG AND SHORT INTERVAL SUMS

AD-A047 906 NORTHROP CORP HAWTHORNE CALIF ELECTRONICS DIV F/G 17/7

COMPUTER PROGRAM PERFORMANCE SPECIFICATION. VOLUME I. RADIO NAV--ETC(U)

JUL 73 N00039-73-C-0209

UNCLASSIFIED NORT-73-48-VOL-1 NL

2 OF 3

AD A047906

Short Sum

$$\frac{\left(\sum_{j=I+KL}^{I+KU} X_j\right)^2 + \left(\sum_{j=I+KL}^{I+KU} Y_j\right)^2}{KU - KL + 1}$$

KL and KU specify the number of 100 ms intervals in burst K; i.e., KU-KL+1 is the number of intervals summed for burst K. See Figure 3.3-4.

Long Sum

$$\frac{\left(\sum_{j=I+KL-2}^{I+KU+2} X_j\right)^2 + \left(\sum_{j=I+KL-2}^{I+KU+2} Y_j\right)^2}{KU - KL + 5}$$

X_j and Y_j are the sine and cosine sum terms, respectively, for the jth 100 ms interval.

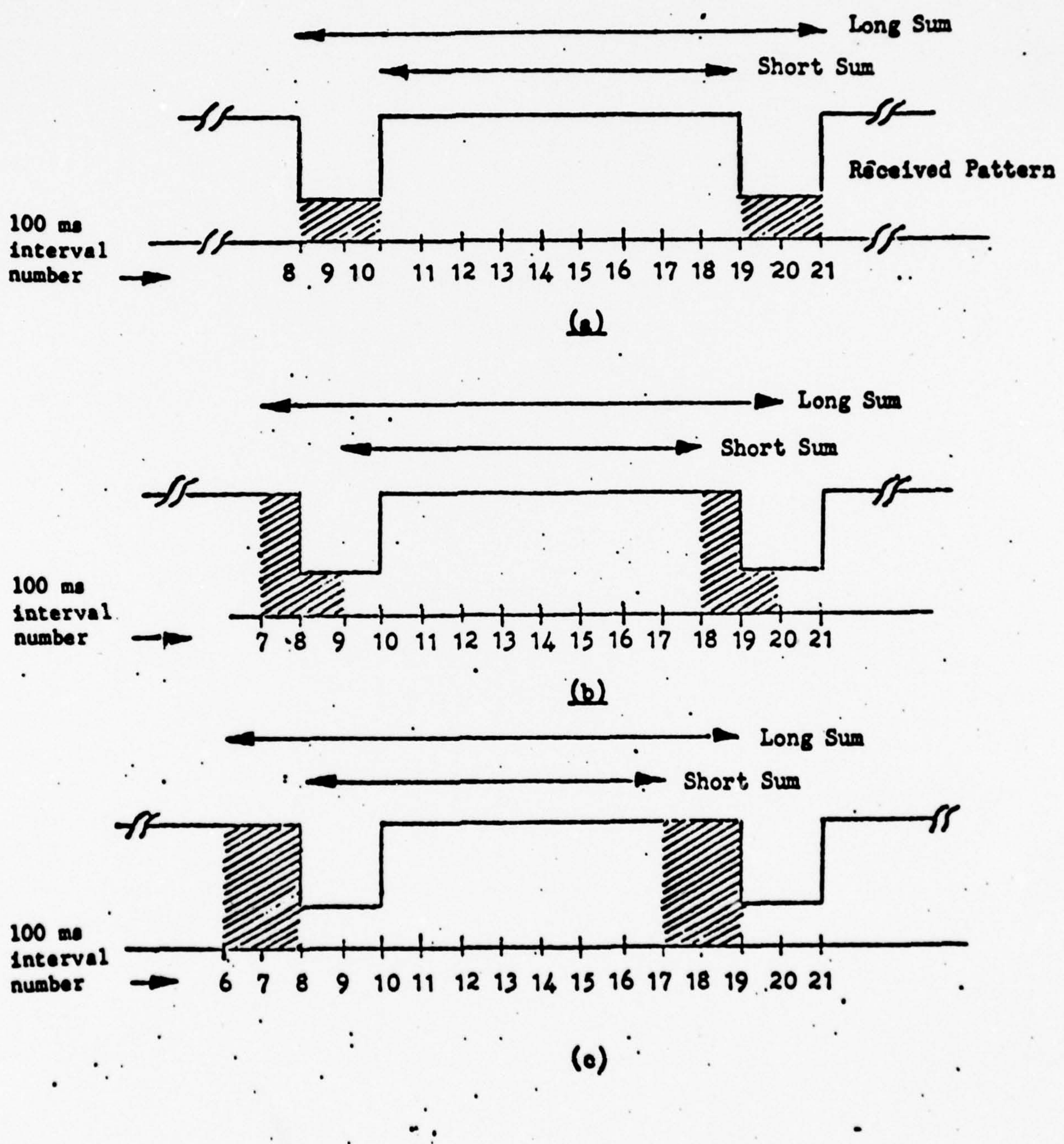
The subscript j on X and Y is modulo 100, ranging 1→100. Thus if I = 95, and KU = 8, then I+KU = 3. Similarly, if I = 1, and KL = 0, I+KL-2 = 99. Also the value KU-KL used in the divisor is computed modulo 100, with a range 9→12.

The long sum is subtracted from the short sum to form a difference.

The differences, one for each station selected in the burst sequence, are added to form C_i, the correlation number for the Ith attempt.

In equation form:

$$C_{I\ (I=1,100)} = \sum_{K=1}^{8} \mathbf{S} \left[\frac{\left(\sum_{j=I+KL}^{I+KU} X_j\right)^2 + \left(\sum_{j=I+KL}^{I+KU} Y_j\right)^2}{KU-KL+1} - \frac{\left(\sum_{j=I+KL-2}^{I+KU+2} X_j\right)^2 + \left(\sum_{j=I+KL-2}^{I+KU+2} Y_j\right)^2}{KU-KL+5} \right]$$



(a) Indicates synchronisation.

(b) and (c) Indicate out of synchronisation.

FIGURE 3.3-4 SYNCHRONIZATION ATTEMPTS

Summation over K means summing the bursts for all stations selected in the OMEGA tableau. KL and KU are determined from the following table, dependent upon the burst number K.

	Slot Number			S	
K	KL_K	KU_K	10.2	13.6	11-1/3
1	0	8	A	H	G
2	11	20	B	A	H
3	23	33	C	B	A
4	36	47	D	C	B
5	50	60	E	D	C
6	63	71	F	E	D
7	74	85	G	F	E
8	88	97	H	G	F

The value of S is 1 or 0 depending upon the allowability of stations. The allowability of stations is determined by STAT MRK_i where i = A, B, ..., H, which is an operator input via the Control-Indicator panel. If station A is disallowed then S = 0 for summation values over K = 1 on 10.2, or K = 2 on 13.6, or K = 3 on 11-1/3. For allowed stations S = 1 over related values of K.

The values of C_I computed in the current attempt at synchronization are added, as they are computed, to a weighted value of the values computed in previous attempts, as follows:

$$C_{I\ ave} = \frac{C_I - C_{I\ last\ ave}}{N} + C_{I\ last\ ave}$$

where N is the number of synchronization attempts.

The values of sine and cosine received during the 0.2 second gap time should sum to approximately zero in the summations $(\Sigma X_i)^2 + (\Sigma Y_i)^2$, and the values in the burst will have a value close to 1. When the correct assumption as to synchronization has been made (i.e., on one of the 100 trials) the assumed pattern will closely correspond to the pattern actually received. In this case, the long sum will contain data from two gaps in its sum, and its average is correspondingly reduced. Further, the short sum contains no slot data, making it and the correlation number C_I, a maximum.

Figure 3.3-4 shows the relationships for in and out of synchronization.

The procedure used, therefore, is to search for a maximum correlation number, and when found, utilize its location (index number) to start synchronization off properly. It is necessary that the computer program has continued to count inputs from the receiver (e.g., counting input buffers) since the data used in the above computations was accumulated, in order to use the correlation information.

Following determination of a maximum C_I^*, there are a number of conditions to be tested to determine success or failure of synchronization. The following procedure will determine synchronization to within $\pm$ 50 ms of the actual case.

These are presented in the following set of logic statements.

a) Determine the four largest C_I^*.

b) Test C_I^* (best) > 0

   If yes, go to c
   If no, go to 1

c) $$C_D = \frac{0.576A^2 + 0.3\, C_I^* \text{ (best)}}{\sqrt{N}}$$

   A = 240 (pulses/0.1 sec)

d) Test $\Delta C = \left[C_I^* \text{ (best)} - C_I^* \text{ (2nd best)} \right] > C_D$

   If yes, go to j

   If no, go to e

e) Test $\left| I_{\text{(best)}} - I_{\text{(2nd best)}} \right| = 1$ or 99

   modulo 1 $\longrightarrow$ 100

   If yes, go to f

   If no, go to 1

f) Test $\Delta C = \left[C_I^* \text{ (best)} - C_I^* \text{ (3rd best)} \right] > C_D$

   If yes, go to g

   If no, go to h

g) This means that the assumed burst pattern is in error by 1/2 of a 100 ms interval; that is, the two best choices are 50 ms either side of the correct choice. Thus the count currently maintained for 100 ms inputs will be adjusted to the average of the two best choices; that is,

$$I_s = \frac{I_{(best)} + I_{2nd\ best)}}{2} \begin{pmatrix}\text{modulo } 100 \\ \text{addition}\end{pmatrix}$$

go to k

h) Test $\left| I_{(best)} - I_{(3rd\ best)} \right| = 1$ or 99

(modulo $1 \longrightarrow 100$)

If yes, go to i

If no, go to l

i) Test $\left| C_I(best) - C_{I(4th\ best)} \right| > C_D$

If yes, go to m

If no, go to l

j) In this case I (best) is accepted as the correct assumption for starting the burst pattern.

Set I_s = I (best)

Go to k.

k) At this point, I_s is the index number indicating at which 100 ms interval the first burst of the assumed pattern (e.g., burst number one) is to start. The count of inputs maintained while the synchronization computations were being made is adjusted by an amount corresponding to I_s, control is passed to burst data processing, and SYNC MRK is set to false.

Also, at this point the "start burst" time, t_{sync} for station A on 10.2 kHz is calculated for the signal input timing processor. t_{sync} will be used to provide the synchronization to the real world for OMEGA software. t_{sync} is always less than 10 seconds; measuring from turn-on time to the <u>first</u> Station A rise time following. The number of 10-second periods elapsing to the true sync time will be adjusted later.

l) This indicates that the synchronization attempt has failed. Input a new 10-second group of data, and reexecute the synchronization computation for the next frequency in sequence.

m) Note that this (and foregoing related tests) tests for the condition in which $C_{I(best)}$, $C_{I(2nd\ best)}$ and $C_{I(3rd\ best)}$ are about equally spaced relative to each other, yet the differences are less than C_D. This will occur if $C_{I(best)}$ is in error by perhaps 25 ms, $C_{I(2nd\ best)}$ by 75 ms, and $C_{I(3rd\ best)}$ by 125 ms. In this case $C_{I(best)}$ is accepted as good in spite of failure of earlier attempts.

Go to j.

<u>Glossary</u>

X, Y	Inputs from the receiver I/O. X represents the time averaged value of sine Ø over 5 ms and Y represents the cosine Ø similarly.
X_K, Y_K	The summation of sine Ø for a period of 0.1 second and cos Ø for 0.1 second.
C_1	The correlation value for the 1<u>th</u> starting point derived on the basis of a single frequency.
I_S	That specific one of the 100-slot intervals that represents the synchronization time.
Ø	The phase angle of the signal processed by the receiver. The value of the phase measurement is not usable due to the use of the pseudo-omni-mode of the orthogonal loop antenna. Only the magnitude of the measurement is useful.
KU	The number of the upper bound on a slot summation for slot number K.
KL	The number of the lower bound on a slot summation for slot number K.
K	The number of the slot for which information is being compiled.
C_I^*	The correlation value for the I<u>th</u> starting point derived on the basis of multiple frequencies.
$C^*_{I\ (best)}$	The largest C_I^*.

Glossary (continued)

C_D	The Confidence Level Constant
t_{sync}	The time at which the leading edge of the first burst arrives for station A on 10.2 kHz, measured from Omega turn-on time.
STAT MRK_i $i=A,B,\ldots,H.$	These markers are input via the Control-Indicator to inform the synchronization routine as to which stations are unavailable.

3.3.1.4 Outputs

Output	Units	Range	Resolution	Destination
SYNC MRK	Marker	----	----	C/I Panel
C_D	$cnts^2/.1$ sec	$0\text{-}10^4$	----	C/I Panel
ΔC	" "	"	----	" "
t_{sync}	Sec.	$0 \rightarrow 15$	0.005	Signal Input Timing Processing; Executive Program

3.3.2 Signal Input Timing

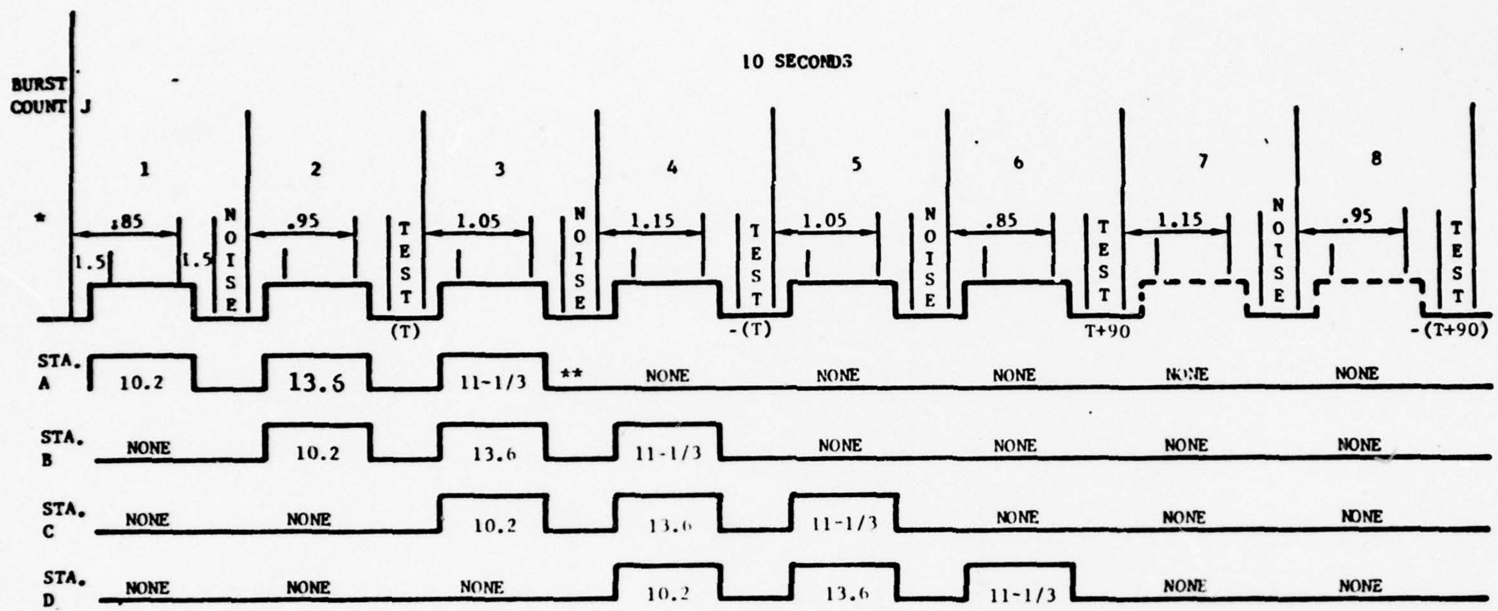
3.3.2.1 Introduction

The stations in the OMEGA network broadcast in a sequential pattern, as is explained in Section 3.1. This pattern is illustrated in Figure 3.3-5.

The bursts and slots are divided into time intervals, as shown in Figure 3.3-6, for purposes of antenna and test selection, accumulating data in the burst and slot intervals, and eliminating unwanted inputs during Start and End Burst.

3.3.2.2 Input

Input	Units	Range	Resolution	Origin
t_{sync}	Sec	0—10	0.005	Synchronization
X_j,Y_j	Counts	$0 \rightarrow 20$	1	I/O

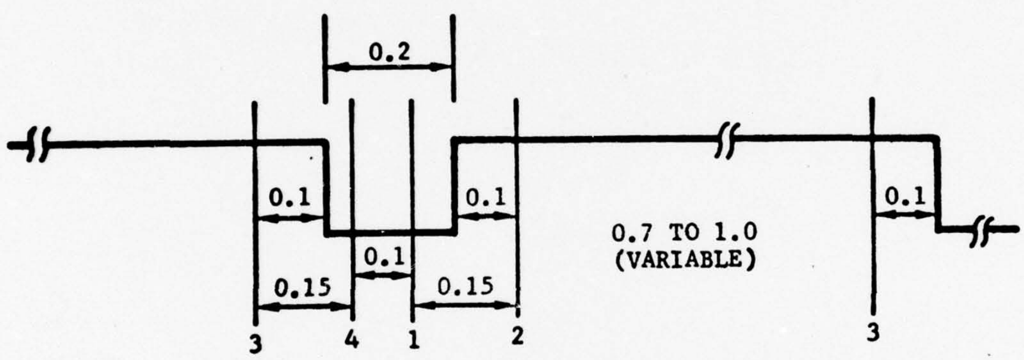


*NUMBERS SHOWN OVER EACH BURST INTERVAL INDICATE LENGTH IN SECONDS OF S.B. + BURST.

**NUMBERS WITHIN THE BURST ENVELOPE FOR INDIVIDUAL STATIONS INDICATE FREQUENCY TRANSMITTED FOR THAT TIME INTERVAL.

10761

FIGURE 3.3-5 BURST PATTERN



Marker	Designation	Interval	Interval Designation
3	END BURST	3-4	END BURST
4	START SLOT	4-1	SLOT
1	END SLOT	1-2	START BURST
2	START BURST	2-3	BURST

10763

FIGURE 3.3-6 BURST/SLOT SEGMENTATION

3.3.2.3 Processing

Data received during the start burst (S.B.) and end burst (E.B.) intervals (Figure 3.3-6) is corrupted by the rise and fall of signal waveform and by transients introduced by antenna and test selection commands. These are therefore waiting periods in which data is not used.

Data received during the burst interval is used to determine phase of the received signal.

Test and calibration data are received in the test slot. This will be used to improve accuracy of calculations made from burst measurement and to provide measurement of variance of phase measurements.

<u>FUNCTIONS EXECUTED BY COMPUTER PROGRAM</u>

<u>Time Marker</u>

1 <u>Completion of Slot Measurement</u>

When either the test or noise measurements have been completed (Paragraphs 3.3.4 , 3.3.5), the measurements must be transferred from the summation registers to those used for computations. These transfers occur at step 1. The values generated during calibration will also be tested for reasonableness. If found to be unreasonable for any frequency, that frequency will not be used. Also at time 1 the antenna switching matrices are set from codes determined by a previous calculation (Paragraph 3.3.3) for the reception of signals during the next burst.

The accumulations of the time averaged values of the sine and cosine of the signal (whether test signals or noise) may be represented as

$$X_m = \sum_{j=1}^{20}{}' \, X_j$$

$$Y_m = \sum_{j=1}^{20}{}' \, Y_j$$

2 <u>Burst Measurement Initiation</u>

At time 2 the summation registers will be cleared. From time 2 to time 3 the burst measurements will be accumulated in these registers.

Time Marker

3 **Completion of Burst Measurement**

When the accumulation of burst data has been completed, the information in the summation registers is used in the burst computations (Section 3.3.7). The set-up for slot time operations is also accomplished at this time. If a noise measurement is to be made during the upcoming slot time TNB is set to Noise and the antenna configuration is alternated between the A and B lobes (assuming the orthogonal loop antenna is used). If a test operation is to be performed, the appropriate one of the four test configurations is sent to the Switching Matrix (TNB set to Test).

The accumulations of the time averaged values of sine Ø and cos Ø over the burst interval may be repesented as:

$$X_m = \sum_{j=1}^{L} X_j$$

$$Y_m = \sum_{j=1}^{L} Y_j$$

where L = 140, 160, 180 or 200 depending upon burst length. (one L count represents 0.005 second worth of data)

4 **Slot Measurement Initiation**

Due to switching transients and signal/noise corruption it is essential that the summation registers be cleared before the actual data accumulation. Test or noise measurements are then initiated which culminate at time 1.

There is an additional function that must be performed at each of the steps indicated in the slot/burst pattern, Figure 3.3-6. That is the computation of the time interval until the next step delineated as $\Delta t \Omega$. The values generated at the time markers 3, 4 and 1 and their subsequent equivalents will be constants as the slot time and all of its elements relative to the Completion of Burst Measurement (time 3) are constant. The times selected at Completion of Burst Measurement and at Completion of Slot Measurement to describe the following time interval will be 0.15 second. The time selected at Slot Measurement Initiation will be 0.1 second.

The time selected at the Burst Measurement Initiation, time 2, will be a variable which is dependent on which of the eight bursts is beginning. The sequence of bursts is depicted in Figure 3.3-5. The effective time of burst will be shorter than shown by 0.2 second for each burst. This is required to allow the circuitry to settle out after changes in the antenna configuration and to bypass the round-off at the start and end times of the burst due to noise.

Definition of Terms

X_j, Y_j — From DMA words 10-22 refer to 3.3.1.2 for the full description which applies up to but not including the indicated summation. The Signal Input timing control will permit appropriate accumulation of these inputs over a slot or burst interval as indicated in the subparagraphs following.

$\Delta t \Omega$ — This is a running variable that controls the initiation of the next event. At event initiation $\Delta t \Omega$ assumes the predetermined value of the time period to the next event.

TNB — Marker to Antenna Switching Matrix denoting a test, noise or burst calculation next.

3.3.2.4 Outputs

Output	Units	Range	Resolution	Destination
$\Delta t \Omega$	Seconds	0.1 - 1.0	0.005	Executive
X_m Y_m	Counts	0 ± 2500	1	3.3.4 Bias, Scale Factor and Phase Shift Calibration 3.3.5 Noise Estimation 3.3.7 Burst Phase Measurement
TNB	Marker	0, 1, 2	--	Antenna Switching Matrix

3.3.3 Antenna Switching Control

3.3.3.1 Introduction

The antenna switching matrix consists of a group of gates for each of the three receiver strips. The function of these gates is to control the signal inputs to the receiver strips. The purpose of the gate control is to permit enhancement of the characteristics of the selected signals. For instance, in measuring phase it is desirable to eliminate one loop of the orthogonal loop antenna, thereby reducing noise and increasing the signal-to-noise ratio. For test and calibration, it is desirable to eliminate antenna inputs entirely.

Each group of gates is furnished with a set of inputs from which combinations are selected. This set of inputs consists of: signals from Loop Antenna A and Loop Antenna B, Loop A-90°, a test signal, and finally the test signal +90°. From this basic set, individual signals or combinations of signals are gated into the summing amplifier according to the basic mode of operation set by the computer.

a) Floater Antenna: When the floater antenna is used, the signal is gated into the receiver strips via loop A input for all modes of operation, except Test and Calibration. The command for this mode of operation is initiated by a manually controlled switch on the Control-Indicator. This switch must be set to FLOAT position. The resulting logic commands the computer to change the antenna switching mode to FLOATER antenna operation.

b) Orthogonal Loop Antenna: The orthogonal loop operation involves four modes of operation:

Mode	Switching Matrix Configuration
1) Synchronization	Select + B and A-90°
2) Phase Measurement	Select + A or +B
3) Test & Calibration	Select T and T-90° alternately
4) Noise and Phantom Estimation	Select + A and + B alternately during slots.

If burst measurements are to be made, the computer will utilize the submarine location, the station location and submarine heading to determine the relative bearing of the station as measured from the sensitive axis of the antenna. This will be used to determine the optimum configuration. If the optimum configuration is + A or + B the matrix is set accordingly and

the data is used as measured. If the optimum configuration is -A or -B (see Figure 3.3-7) the matrix is set to +A or +B appropriately and the measured phase is shifted by 180° in the computer program. The summation registers are cleared at the start of the burst measurement.

3.3.3.2 Inputs

Input	Units	Range	Resolution	Origin
TNB	Marker	---	---	Signal Input Timing
FLOAT	Marker	---	---	C-I Switch
Θp	Radians	0 -± π	2^{-15}	Navigation
ψ_A	Radians	0 -± π	2^{-15}	Navigation
$[r_{ij}]_{MATRIX}$	Unitless	0 -±1	2^{-30}	Navigation

3.3.3.3 Processing

a) Does TNB marker indicate test input?

Yes: Determine whether test or test quadrature is scheduled. Set RX(T) or RX(TQ) = true accordingly. Exit.

No: Continue.

b) Does TNB marker indicate noise input?

Yes: Then is FLOAT marker = true?
If so, then RX(A) = true
If not, then determine whether Loop A or Loop B is scheduled for noise input. Set RX(A) or RX(B) accordingly. Exit.

No: Continue.

c) Does TNB marker indicate burst input?

Yes: Then is FLOAT marker = true?
If so, then RX(A) = true
If not, then continue.

d) Determine which stations are transmitting on which frequency and obtain station coordinate vectors D_i from data base.

e) Calculate ψ_B, the bearing to the station selected (north to heading vector CW positive)

$$\psi_B = -\tan^{-1}\left(\frac{-D_i \cdot R_2}{D_i \cdot R_3}\right) - \theta_P$$

where R_i are the system computation axes:

$\hat{R}_1$ is the local vertical,

$\hat{R}_3$ is the reference azimuth axis

$\hat{R}_2$ is $\hat{R}_3 \times \hat{R}_1$

θ_P is the system azimuth angle between north and R_3 CCW positive.

$\hat{D}_i$ are vectors describing station locations on earth's surfaces using earth axes as reference frame.

f) Calculate θ_{BR} the relative bearing to a selected point measured from the effective A-loop antenna center line to bearing CW positive.

$$\theta_{BR} = \psi_B - \psi_A \quad -180^\circ$$

Where ψ_A is submarine heading measured north to the centerline clockwise (CW) positive.

g) Referring to Figure 3.3-7:

If $315^\circ < \theta_{BR} < 45^\circ$, set RX(A) = true, set $\phi' = 0^\circ$.

If $225^\circ < \theta_{BR} < 315^\circ$, set RX(B) = true and set $\phi' = 180^\circ$.

If $135^\circ < \theta_{BR} < 225^\circ$, set RX(A) = true and set $\phi' = 180^\circ$.

If $45^\circ < \theta_{BR} < 135^\circ$, set RX(B) = true and set $\phi' = 0^\circ$.

Where ϕ' will invert the phase in the Burst Processing equations and RX(A) and RX(B) markers will command the antenna switching matrix via DMA I/O.

3.3.3.4 Outputs

Output	Units	Range	Resolution	Destination
LOBE	Marker	--	---	3.3.6 Phantom Phase Calculations
ϕ'	Radians	0 to $\pm\pi$	2^{-15}	3.3.7 Burst Phase Measurements
RX(A) RX(B) RX(T) RX(TQ)	Markers	--	---	Receiver Antenna Switching Matrix via DMA I/O

3.3.4 <u>Bias, Scale Factor and Phase Shift Calibration</u>

3.3.4.1 Introduction

The receiver correlators may have a bias and there may be hardware-induced phase shifts. These anomalies, which could introduce error into the estimate of phase, will be removed by the procedures following. Also, the phase shifts introduced by the antenna and couplers are removed.

There are eight slots in the 10-second OMEGA cycle. Four are reserved for noise measurements, the other four for the test and calibration signals. For each transmission frequency there will be injected into the antenna switching matrices the following: Test (T), minus Test (-T), Test plus 90° (T+90), and minus Test plus 90° (-(T+90)). One of these four signals will be introduced at every other slot period. At the end of the 10-second cycle the Bias and Scale Factor calculations will be made, the known phase shifts removed and the results tested for credibility.

3.3.4.2 Inputs

X_m, Y_m Summation of 5 ms input values (on each frequency) from the receiver, each pair of which are time averaged functions of the sine and cosine, respectively, of the Test signals injected during slot periods on each channel.. (See paragraph 3.3.2).
Quantity: 12 pairs per 10-second OMEGA cycle
Timing: 3 pairs every other slot period.

Input	Units	Range	Resolution	Origin
X_m, Y_m	Counts	0 to ±2500	1	Signal Input Timing

3.3.4.3 Processing

The following procedure is indicated for one channel only. It must be done three times in all (once for each frequency) in each 10-second OMEGA cycle.

a) At test slot time i (i = 1, 4) obtain the sine and cosine measurements of the injected test signals

$$X_{ci} = X_m$$

$$Y_{ci} = Y_m$$

$$\Delta t_c = 0.1 \text{ sec}$$

The results are as follows:

X_{c1}, Y_{c1}	Sine (T)	, cosine (T)
X_{c2}, Y_{c2}	Sine (-T)	, cosine (-T)
X_{c3}, Y_{c3}	Sine (T+90)	, cosine (T + 90)
X_{c4}, Y_{c4}	Sine (-(T+90))	, cosine (-(T+90))

b) At end of last test slot, and noting that Y_{c4} and Y_{c3} are, by trigonometric identity, functions of the sine; and similarly that X_{c3} and X_{c4} are functions of the cosine:

$$\phi_o = \tan^{-1}\left[\frac{X_{c1} - X_{c2} + Y_{c4} - Y_{c3}}{X_{c3} - X_{c4} + Y_{c1} - Y_{c2}}\right] + \phi_{CALIB}$$

where ϕ_{CALIB} is a constant whose value is a combination of values dependent upon the phase shift characteristics of the couplers and antenna used.

$$\phi_{CALIB} = \phi_{OMEGA\ COUPLER} + \begin{cases} \phi_{FLOATER/ACU1441} \text{ or} \\ \phi_{LOOP\ ANT/ACU1441} \end{cases}$$

The following table summarizes the values.

	$\phi_{OMEGA\ COUP}$	$\phi_{FLOAT/ACU1441}$	$\phi_{LOOP/ACU1441}$
Frequency 10.2	1 cec	-90 cec	-17.8 cec
13.6	1.5 "	18 "	9.8 "
11-1/3	1.5 "	2 "	- 5.7 "

c) Calculate the filtered bias of the X and Y channels, using a 200 second-time constant low pass filter and check for credibility.

$$B_{XM} = \frac{1}{4}(X_{c1} + X_{c2} + X_{c3} + X_{c4}) / \Delta tc \quad \text{counts/sec.}$$

$$B_{YM} = \frac{1}{4}(Y_{c1} + Y_{c2} + Y_{c3} + Y_{c4}) / \Delta tc \quad \text{counts/sec.}$$

$$B_X = B_X + (B_{XM} - B_X) \times .05$$

$$B_Y = B_Y + (B_{YM} - B_Y) \times .05$$

Is $|B_X| < N_B$? $\quad N_B = 250$ counts

NOTE: The time constant of 200 seconds is due to the gain of .05 and an iteration rate of 0.1 times per second.

If not, indicate SYSTEM FAIL = true and continue;

If so, continue

Is $|B_Y| < N_B$?

If not, indicate SYSTEM FAIL = true and continue;

if so, continue.

d) Calculate the scale factors of the X and Y channels and check for credibility.

$$A_X = \frac{1}{2}\left[(X_{c1} - X_{c2})^2 + (X_{c3} - X_{c4})^2\right]^{\frac{1}{2}} \times \frac{1}{\Delta tc} \text{ counts/sec}$$

$$A_Y = \frac{1}{2}\left[(Y_{c1} - Y_{c2})^2 + (Y_{c3} - Y_{c4})^2\right]^{\frac{1}{2}} \times \frac{1}{\Delta tc} \text{ counts/sec}$$

Test: Is $|A_X - A_{CALIB}| < N_A$?

$N_A = 500$ counts

$A_{CALIB} = 1600$ counts

If not, increment Calibrate Fail Count. If Calibrate Fail Count >5, indicate SYSTEM FAIL = true and continue;

If so, set Calibrate Fail Count to zero and continue.

TEST: IS $|A_Y - A_{CALIB}| < N_A$?

If not, increment Calibrate Fail Count. If Calibrate Fail Count >5, indicate SYSTEM FAIL = true and continue;

If so, set Calibrate Fail Count to zero and continue.

3.3.4.4 Outputs

a) A_X, A_Y, B_X, B_Y Scale Factors and Bias for each channel.

Quantity - 12 (one set per frequency)

Timing - one set of 6 per 10-second OMEGA cycle.

b) ϕ_o Hardware phase shift

Quantity - 3 (one per frequency)

Timing - One set of 3 per 10-second OMEGA cycle.

c) SYSTEM FAIL: Marker

Timing - Upon failure.

Output	Units	Range	Resolution	Destination
A_X, A_Y	$\frac{counts}{sec}$	$0 \rightarrow 2500$	1/2	Burst Phase Measurement
B_X, B_Y	$\frac{counts}{sec}$	$0 \rightarrow \pm 250$	1/2	" " "
ϕ_o	Rad.	$0 \rightarrow \pm \pi$	2^{-31}	" " "
System Fail	Marker	---	---	Control-Indicator Display

3.3.5 Noise Estimation (Q_t)

3.3.5.1 Introduction

This routine is used to estimate system-external noise. The output will be used to determine credibility of the next two burst measurements on the pertinent frequency. If noise is high, then little weight is given these measurements. Conversely, if low, then the burst measurements are considered accurate.

This is not a linear estimate. If noise is above a criterion value it is amplified to assure credibility of next two bursts. If low and the last noise measurement was high, then the new value is sharply reduced to a reasonable level. If both previous and current values are low, then the new value of Q_t is a smoothed value of the old.

3.3.5.2 Inputs

X_m, Y_m summation of input values from the receiver which is a function of the sine and cosine (respectively) of the received signal on a channel (10.2, 13.6, or 11-1/3). Here, a summation over a slot. (See 3.3.2.)

A_x, A_y Scale factor values from calibration routine during last 10-second cycle

B_x, B_y Bias value from calibration routine

Timing: This routine is done at every other slot time and for each frequency.

Limits: (non linear): when current noise level (Q_t') is greater than 0.05-second, then sharp amplification occurs. If old value (Q_t) is greater than, but new value is less than 0.05-second, then old value endures a sharp deamplification. If current and old value low, then new value is smoothed old value.

Input	Units	Range	Resolution	Origin
X_m, Y_m	Counts	0±2500	1	Signal Input Timing
A_x, A_y	$\frac{\text{Counts}}{\text{Sec}}$	0-2500	1/2	Scale Factor and Phase Shift Calibration
B_x, B_y	$\frac{\text{Counts}}{\text{Sec}}$	0±2500	1/2	

3.3.5.3 Processing

a) Take sine and cosine values of incoming signals from receiver taken over a slot period (between bursts) and remove scale factors and bias.

$$X_N' = \frac{X_m - B_x \Delta t_c}{A_x} \quad \text{Counts/.1 seconds}$$

$$Y_N' = \frac{Y_m - B_y \Delta t_c}{A_x} \quad \text{Counts/.1 seconds}$$

Note: Δt_c = .1 seconds.

b) Obtain rough measurement of noise (Q_t).

$$Q_t' = \frac{\left(X_N'\right)^2 + \left(Y_N'\right)^2}{\Delta t_N} \qquad \text{Note: } \Delta t_n = .1 \text{ seconds.}$$

c) Now test Q_t' to see whether larger than criterion value $Q_{to} = 0.05$

<u>If so</u>, then amplify this number. This will later deemphasize credibility of next two burst measurements due to excessively high noise.

$$Q_t = 9\,Q_t' - 0.4$$

Exit.

<u>If not</u>, (if $Q_t' < 0.05$) then:

d) Test old value to see if it was reasonable.

is $Q_t < Q_{to}$

<u>If so</u> then smooth by using old value of Q plus fraction of Q.

$$Q_t = Q_t + K_Q\,(Q_t' - Q_t) \quad \text{where } K_Q = 0.05$$

Exit.

If not

Then reduce sharply to reasonable level.

Let $Q_t = 0.025$

And $Q_t = Q_t + K_Q\ (Q_t^{'} - Q_t)$

Exit.

Initialization Note: Due to A_x, A_y inputs, this process for noise estimation will not begin until after calibration.

3.3.5.4 Outputs

Output	Units	Range	Resolution	Destination
Q_t	Sec	0-1	2^{-14}	Burst Phase Measurement
$X_N^{'}\ Y_N^{'}$	Sec	0 -± 1	2^{-14}.	Phantom Calibration

Note: There are three pairs of X_N, Y_N corresponding to the three frequencies. There are three corresponding values of Q_T.

3.3.6 Phantom Calculation Calibration

3.3.6.1 Introduction

In some cases the interaction of the hardware components produces a non-transient phase which must be detected (if it exists) on each frequency and rejected. This is done by a phase measurement during a slot interval (between bursts; see 3.3.2) then removing these spurious signals during burst-phase calculations.

3.3.6.2 Inputs

Input	Units	Range	Resolution	Origin
Y_N', Y_N'	Sec	$0 \rightarrow \pm 1$	2^{-14}	Noise estimation
LOBE	Marker	-	-	Antenna Switch Control

Above data available on all three frequencies. This routine will be done at every other end-of-slot period. X_N',Y_N' are unitless as they represent sine and cosine respectively.

3.3.6.3 Processing

This is a simple filtering device (with a time constant of 5000 seconds) which will track the phase phantom. Since the phantom is constant, this simple filtering device suffices. The phantom measurement will be calculated as indicated below for each frequency.

For X channel (sine function)

Either: $X_{PA} = .001 \left(X_N' \times \frac{1}{\Delta t_N} - X_{PB}\right)$; when A Lobe selected

Or: $X_{PB} = .001 \left(X_N' \times \frac{1}{\Delta t_N} - X_{PB}\right)$; when B Lobe selected

Note: $\Delta t_N = 0.1$ second

For Y channel (cosine function)

Either: $Y_{PA} = .001\ (Y_N' \times \frac{1}{\Delta tn} - Y_{PB})$; when A Lobe selected

Or: $Y_{PB} = .001\ (Y_N' \times \frac{1}{\Delta tn} - Y_{PB})$; when B Lobe selected

Initialization Note: Because of dependency on noise estimation, this procedure cannot begin until after calibration.

3.3.6.4 Outputs

Output	Units	Range	Resolution	Destination
X_{PA}, X_{PB} Y_{PA}, Y_{PB}	Sec	0 - ±1	2^{-14}	Burst Phase Measurement

These outputs are preserved from day to day.

3.3.7 Burst Phase Measurement

3.3.7.1 Introduction

The phase sinusoids from the receiver will be processed by the procedure following to yield a phase representation in radians. The hardware phase shifts, correlator bias and scale factor, calculated elsewhere, will be removed here as will any phantom phase anomalies.

The variance of the phase angle which represents the credibility assigned to the incoming data will also be calculated.

3.3.7.2 Inputs

From DMA input (words 17-22):

X_m, Y_m Summation of input sine and cosine values from the receiver which represent the phase of the received burst on each one of the three frequencies. (See Paragraph 3.3.2).

Quantity: 24 pairs per 10-second OMEGA cycle.

Timing: 3 pair per burst period.

Input	Units	Range	Resolution	Origin
X_m, Y_m	Counts	0-±2500	1	DMA I/O words 17-22
A_x, A_y	$\frac{\text{Counts}}{\text{Sec}}$	0-2500	1/2	Bias, scale factor and phase shift calibration
B_x, B_y	$\frac{\text{Counts}}{\text{Sec}}$	0-±250	1/2	Bias, scale factor and phase shift calibration
X_{PA}, X_{PB} Y_{PA}, Y_{PB}	Unitless	0-±1	2^{-14}	Phantom phase calibration
ϕ'	radians	0-±π	$2^{-15}\pi$	Antenna switching control
ϕ_o	radians	0-±π	$2^{-15}\pi$	Bias; scale factor and phase shift calibration
Q_t	sec	0-1	2^{-14}	Noise estimation
LOBE	marker	-	-	Antenna switch control
Δt_B	seconds	.7-1.0	0.005	Station burst times table

3.3.7.3 Procedures

The following procedure will be repeated 24 times for each station-frequency pair in the 10-second OMEGA cycle.

a) Correct incoming burst measurements for correlator bias and apply scale factor

$$X_B' = \frac{X_m - B_x \Delta t_B}{A_x}$$

$$Y_B' = \frac{Y_m - B_y \Delta t_B}{A_x}$$

b) Correct measurements for spurious phase signals (phanthoms)

Either

$$\left.\begin{aligned} X_B &= X_B' - X_{PA} \Delta t_B \\ Y_B &= Y_B' - Y_{PA} \Delta t_B \end{aligned}\right\} \text{If A lobe was used to receive signals}$$

Or

$$\left.\begin{aligned} X_B &= X_B' - X_{PB} \Delta t_B \\ Y_B &= Y_B' - Y_{PB} \Delta t_B \end{aligned}\right\} \text{If B lobe was used to receive signals}$$

c) Compute the phase angle ϕ_m and subtract ϕ_o, the phase shift introduced by the hardware, then add ϕ' which corresponds to either 0^o or 180^o depending upon whether the inverse or obverse antenna lobe was used.

$$\phi_m = \text{TAN}^{-1}\left(\frac{X_B}{Y_B}\right) - \phi_o + \phi'$$

d) Calculate $\sigma^2_{\phi_m}$ the computed variance of the phase angle measured at the burst level. To do this Q_m, the burst element of phase variance, is used together with Q_t, the noise measurement taken during a previous slot. This mathematical comparison of Q_t and Q_m yields $\sigma^2_{\phi_m}$ which is a function of the signal-to-noise ratio and therefore a measure of the trustworthiness of the phase measurement obtained (ϕ_m).

$$Q_m = \frac{X_B^2 + Y_B^2}{\Delta t_b}$$

$$\sigma^2_{\phi_m} = \frac{Q_t\left(\Delta t_b - Q_m\right)}{2\,\Delta t_b\left(Q_m - Q_t\right)} + \frac{1}{4}\ \text{cec}^2$$

Here, 1/4 cec^2 is added to achieve a minimum value for $\sigma^2_{\phi_m}$.
Δt_b = time span over which burst was measured.

Initialization Note: Burst phase processing will not begin until after phantom and noise equations have been processed.

3.3.7.4 Outputs

Output	Unit	Range	Resolution	Destination
ϕ_m	cycles	0-±1/2	2^{-32}	Tracking filters and Control-Indicator Panel
$\sigma^2_{\phi_m}$	cycle^2	0-1	2^{-31}	Tracking filters
Q_m	sec	0-1	2^{-14}	Base station selection

Note: There are 24 pair of $\left(\phi_m, \sigma^2_{\phi_m}\right)$ transferred to tracking filters per 10-second OMEGA cycle; 3 pair per burst period. $\sigma^2_{\phi_m}$ is limited between $\frac{1}{4}\ \text{cec}^2$ and 1 cycle.

3.3.8 Base Station Selection

3.3.8.1 Introduction

The burst phase calculation (paragraph 3.3.7) will yield the first rough estimates of phase and signal variance from each station and on each frequency. However, the tracking filters track phase differences between each station and another which has been designated as the base station. The computer program designates one of the four stations as the base station when its three frequency signal strength is largest.

3.3.8.2 Inputs

Input	Units	Range	Resolution	Origin
Q_m	sec	0-1	2^{-14}	Burst phase measurement

Quantity: One for each station-frequency pair (24)

Timing: Three for each burst period.

3.3.8.3 Processing

3.3.8.3.1 Processing Data From a Non-Base Station "i:"

a) Computer program determines that station "i" is a usable station and that it has finished the third (and last) burst for the current 10-second broadcast cycle. The phrase usable station means a station not deselected by operator and not within 400 miles.

b) Form Q_m product for station i.

Let $RH_i = Q_{mi}(10.2) \times Q_{mi}(13.6) \times Q_{mi}(11\text{-}1/3)$

c) Perform a simple smoothing operation on resultant

$$SRH_i = SRH_i + 0.1\,(RH_i - SRH_i)$$

d) Compare with base station value for SRH. Note that base station SRH value is amplified by 1.1 to prevent frequent changes of base station.

If $SRH_i > SRH_{base} \times 1.1 + HYSTERESIS$

Then designate station i as new base station,
BASE Marker = i
Set RESET marker 0 to tracking filters,
Wait 10 seconds and set START marker 0 to tracking filters.

Otherwise continue with current base station.

In the above, HYSTERESIS is a term which may be used when operating in an area where all OMEGA transmissions are weak. Current value of HYSTERESIS is zero.

3.3.8.3.2 Processing the Base Station Data

a) Perform steps a, b, and c, in 3.3.8.3.1

b) If $SRH_{base} \leq 0.0078125$, then set SIG LOSS marker and continue normal operation, otherwise continue.

3.3.8.4 Outputs

Output	Units	Range	Resolution	Destination
RESET TF	Marker	-	-	Tracking Filter
START	Marker	-	-	Tracking Filter
BASE	Identifier	A,B,---H,	-	Phase difference function, tracking filters, combinational filter, control indicator

RESET TF = true upon change of base station; START = true 10 seconds following.

3.3.9 Phase Difference Function

3.3.9.1 Introduction

There is an induced phase shift on the incoming OMEGA signals which is a function of the underwater depth of the antenna. This means that a slight change in submarine depth manifests itself by a drastic shift in indicated position. This situation is ameliorated on each frequency by differencing any measured signal with one from another station, thus subtracting out the depth-induced phase shift.

The procedure for this is to select one station as base and then to difference all incoming signals with the base on the required frequency. The selection of base is discussed in 3.3.8, Base Station Selection.

3.3.9.2 Inputs

ϕ_m $\sigma^2_{\phi_m}$ Phase measurements and associated variances from burst phase processing

Quantity: 24 pair per 10-second cycle

Timing: 3 pair per burst period

BASE: Identifier for base station

Quantity: One

Timing: Upon change of base

Input	Units	Range	Resolution	Origin
ϕ_m	cycles	0-±1/2	2^{-32}	Burst Phase Measurement
$\sigma^2_{\phi_m}$	cycle^2	0-1	2^{-31}	Burst Phase Measurement
BASE	identifier	A,B,---H,	-	Base Station Selection

3.3.9.3 Processing

The following procedures, though indicated for one input only, are done three times per each burst period; 24 per 10-second OMEGA cycle.

Determine station and frequency of input. Is input phase measurement from base station? (check BASE)

No. Then difference input phase measurement ϕ_a with last stored base station phase value ϕ_b, where ϕ_i represent ϕ_m, station i on associated frequency; from burst processing.

$$\phi_{ab} = \phi_a - \phi_b$$

Then combine the associated variances as indicated.

$$\sigma^2_{ab} = \sigma^2_a + \sigma^2_b$$

where σ^2_i represents $\sigma^2_{\phi_m}$ station i on associated frequency; from burst processing.

Yes. Then difference input base station measurement with last stored base station phase value. Combine the variances as indicated.

$$\phi_{bb} = \phi_b\text{(input)} - \phi_b\text{ (stored)}$$

$$\sigma^2_{bb} = \sigma^2_b\text{ (input)} + \sigma^2_{bb}\text{(stored)}$$

Then replace reference base station phase value and variance with input falues.

3.3.9.4 Output

Output	Units	Range	Resolution	Destination
ϕ_{ab} or ϕ_{bb}	cycles	0-±1/2	2^{-32}	Tracking filters
σ^2_{ab} or σ^2_{bb}	cycle^2	0-1	2^{-31}	Tracking filters

Quantity: 24 per 10-second OMEGA cycle

Timing: 3 per burst period.

3.3.10 Tracking Filters

3.3.10.1 Introduction

It is desirable to further process the measurements from the Phase Difference Algorithm (PDA) in order to develop more accurate and usable values. This is accomplished in the tracking filters. Successive phase difference measurements from the PDA for each transmitting station and base and each frequency are combined in separate tracking filters. Since there are eight (8) possible transmitting stations and three (3) frequencies processed in the receiver, there are twenty-four (24) tracking filters. Each tracking filter receives an input from the PDA every ten (10) seconds. This input consists of a measure of phase difference ϕ_{ik}(freq) and a computed variance of this measurement σ^2_{ik} (freq). This measured phase difference ϕ_{ik} (freq) is then compared (or weighted in a statistical sense) with an estimated value of phase $\hat{\phi}_{ik}$ (freq) which the tracking filter computes based upon previous measurements. From this comparison a new estimate of phase is computed.

Henceforth the frequency dependence of the symbols will be dropped for convenience, so that ϕ_{ik} (freq) will be represented as ϕ_{ik}. It is understood that the operations involved apply to not one but three frequencies.

In order to compare or statistically average successive phase difference measurements spaced 10 seconds apart in time, it is necessary to remove the effect of the change in phase due to the submarine change in position. This is referred to as rate-aiding. Velocity information is obtained from a velocity source external to the OMEGA receiver (E.M. Log Repeater or manual insert). The velocity inputs to the tracking filter consist of the V_2 and V_3 components of the raw velocity as computed by the velocity processing equation. OMEGA velocity corrections are not used in tracking filters. The tracking filter then computes the component of velocity along the direction from submarine to transmitting station, then to the base station, and then converts to an equivalent dead reckoning phase rate, $\dot{\phi}_{DR}$. This phase rate is then used to update the tracking filter phase-difference estimate $\hat{\phi}$.

Besides estimating phase differencies, the tracking filter also estimates phase-difference rate error, $\Delta\dot{\phi}$. This is the error in phase rate as computed from the velocity sources. The estimated phase-difference rate error $\widehat{\Delta\dot{\phi}}$ is used to correct the computed phase-difference rate $\dot{\phi}_{DR}$ in the time update of the estimate.

In addition to computing $\hat{\phi}$ and $\Delta\hat{\dot{\phi}}$, the tracking filter also computes the following variances:

a) $\sigma^2_{\phi\phi}$, the variance of the error in estimating phase difference

b) $\sigma^2_{\dot{\phi}\dot{\phi}}$, the variance of the error in estimating phase difference rate error

c) $\sigma^2_{\phi\dot{\phi}}$, the cross variance of errors in estimating both

It is the computation of these variances along with σ^2_{ij} from burst measurements that allows the filter to statistically average ϕ_{ij} and $\hat{\phi}_{ij}$ and obtain better estimates of $\hat{\phi}_{ij}$ and $\Delta\dot{\phi}_{ij}$. The three variances listed above are updated and recomputed at every phase measurement.

The outputs of the tracking filters are $\hat{\phi}$, $\sigma^2_{\phi\phi}$ (station and base subscripts omitted) for each station-base or base-base pair. These outputs are the inputs to the combinational filter. The combinational filter combines the outputs of the tracking filters to obtain position estimates. When $\sigma^2_{\phi\phi}$ has reached a value of less than 3 cec^2 and $\sigma^2_{\dot{\phi}\dot{\phi}}$ is less than (0.09 cec/sec)^2 for three consecutive burst filter measurements, the phase estimate is considered accurate enough to be used by the combinational filter. A counter (called the n counter) is used as a flag to tell the combinational filter when to read the tracking filter outputs. With every PDA measurement the counter is incremented if $\sigma^2_{\phi\phi}$ and $\sigma^2_{\dot{\phi}\dot{\phi}}$ are both less than their respective limits, otherwise the counter is reset to zero. When the counter reaches three the tracking filter is ready to be read. The combinational filter will then read the $\hat{\phi}$ and $\sigma^2_{\phi\phi}$ from the tracking filter. Until the tracking filter outputs are read the tracking filter continues to operate in a normal manner. When the outputs are read, the n counter is reset to zero and the tracking filter is reset. It is desirable for each reading from a given tracking filter to be statistically independent from the others. For this reason the tracking filter variances are reset to their initial values after being read by the combinational filter. These values assure independence of tracking filter outputs.

The statistical derivation of the tracking filter equations is given in Appendix A.

3.3.10.2 Inputs

Inputs	Units	Range	Resolution	Origin
V_2, V_3	ft/sec	0-±4096	2^{-3}	Velocity & Heading Processing
ϕ_{ik}	cycles	0-±1/2	2^{-32}	Phase Difference Function
σ^2_{ik}	$cycle^2$	0-1	2^{-31}	Phase Difference Function
$\phi_{pp_{ik}}$	cycles	0-1024	2^{-21}	Propagation Prediction
Reset TF	Marker	----	----	Base Station Selection
Start	"	----	----	" " "

Notes: V_2, V_3 Limits: 0-35 knots

For ϕ_{ik}, σ^2_{ik} If $i \neq k$ then a station-base pair.

If $i = k$ then a base-base pair.

(k determined by base-station-selection)

24 pairs input in 10-second OMEGA cycle;
3 pair per burst period.

3.3.10.3 Processing

There are four distinct operations associated with the tracking filters:

- Initialization/reinitialization
- Time updating
- Phase rate updating
- Measurement/updating

a) <u>Initialization/reinitialization</u>

1) The Initialization/reinitialization procedures are used:

   a. At start up

   b. When the velocity sources for the calculations are changed

   c. When the combinational (Kalman) filter uses a tracking filter output (Note: done within the Kalman Filter Subprogram)

   d. Whenever a change in the base station is indicated

   e. Whenever initial time or initial position is entered.

2) The procedures for the above are as follows:

   a. Set all n-counters to zero

   b. Set $\sigma^2_{\phi\phi} = \frac{1}{12}$

   c. Set $\sigma^2_{\phi\dot{\phi}} = 0$

   d. Set $\sigma^2_{\dot{\phi}\dot{\phi}} = (0.006\pi)^2$ or $(.003 \text{ cycle/sec})^2$

   For 1a, 1d, 1e; reset all tracking filters by 2a through 2d.

   For 1b; reset all tracking filters by 2c and 2d.

   For 1c; reset only the selected filter, using 2a through 2d.

b) <u>Variance Time Update</u>

All tracking filters are time updated at the end of every OMEGA burst. The following equations are computed in the order indicated.

1) $\sigma^2_{\phi\phi}(k) = \sigma^2_{\phi\phi}(k-1) + 2\,\sigma^2_{\phi\dot{\phi}}(k-1)\,\Delta t_k + \sigma^2_{\dot{\phi}\dot{\phi}}(k-1)\,(\Delta t_k)^2$

Test: is $\sigma^2_{\phi\phi}(k) > 1\ (\text{cycle})^2$

Yes. Then set $\sigma^2_{\phi\phi}(k) = 1\ (\text{cycle})^2$

$$\sigma^2_{\phi\dot{\phi}}(k) = \sigma^2_{\phi\dot{\phi}}(k-1)/2$$

go to (2)

No. Then $\sigma^2_{\phi\dot{\phi}}(k) = \sigma^2_{\phi\dot{\phi}}(k-1) + \sigma^2_{\dot{\phi}\dot{\phi}}(k-1)\,\Delta t_k$

2) $\sigma^2_{\dot{\phi}\dot{\phi}}(k) = \sigma^2_{\dot{\phi}\dot{\phi}}(k-1) + r^2$

Test: is $\sigma^2_{\dot{\phi}\dot{\phi}}(k) > \frac{1}{2\pi^2} \left(\frac{\text{cycle}}{\text{sec}}\right)^2$

Yes. Then set $\sigma^2_{\dot{\phi}\dot{\phi}} = \frac{1}{2\pi^2}$

$$\sigma^2_{\phi\dot{\phi}}(k) = \frac{\sigma^2_{\phi\dot{\phi}}(k)}{2}$$

and continue.

No. Then continue.

c) <u>Phase Rate Update</u>

Processed after variance update for each station and base-station pair.

1) Station coordinates; earth fixed to local level coordinates. Obtain for station and base.

$$SL_{2i} = \sum_{f=1}^{3} r_{2f}\, S_{fi}$$

$$SL_{3i} = \sum_{f=1}^{3} r_{3f} \, S_{fi}$$

i = 1, ... 8 (station)

rij = Element in the i^{th} row and j^{th} column of the R_{ij} matrix from which vehicle position is computed.

2) $\dot{\phi}_{DR}$ Determination; obtain $\dot{\phi}_{DR}$ (station) and $\dot{\phi}_{DR}$ (base)

$$\dot{\phi}_{DR_{ii}} = \frac{V_3 \, SL_{3i} + V_2 \, SL_{2i}}{\left(SL_{3i}^2 + SL_{2i}^2\right)^{1/2}}$$

Since the filters are tracking an angle that represents the phase of station i at time t minus the phase of the base station at some earlier time, it is necessary to make the following correction for arrival at the final value of $\dot{\phi}_{DR}$ for each tracking filter

$$\dot{\phi}_{DR_{ik}} = \dot{\phi}_{DR_{ii}}(t) - \dot{\phi}_{DR_{kk}}(t-t')$$

where
- i = station number
- j = frequency
- k = base station number
- t = time
- t' = time delay between base station burst and station i burst for this frequency (if i=k then t-t= 10 sec)

For computational purposes it would be adequate to set $t' = 0$ in all cases.

3) Phase Estimate Update

The phase difference estimate is iterated once for each station and base station combination at the end of each burst (24 times at end of each burst).

$$\hat{\phi}(k) = \hat{\phi}(k-1) + \Delta t_u \left[\frac{\lambda 3}{\lambda i} \dot{\phi}_{DR}(k) + \widehat{\Delta\phi}(k-1)\right]$$

where Δt_u = time period since last update.

If Δt_b is interval of previous burst then

$\Delta t_u = \Delta t_b + 0.4$ sec.

4) Integral Lane Count Check: Periodically the tracking filter will compare its phase difference estimate (in cec's) with the phase difference estimate from the propagation prediction routine. The steps to this procedure are as follows:

a. Compare fractional phase difference value of tracking filter with that from propagation prediction (pp).

b. Incorporate integer number of lanes from pp value, $\pm$ 1 lane if necessary, to ensure tracking filter integer-decimal value is within a 1/2 lane of pp value.

d) Measurement Update

A measurement update occurs if the variance from the PDA is less than one square cycle. The difference between the estimate of phase difference $\hat{\phi}$, and the raw measurement, ϕ_{ik}, is used to make the filter adaptive; the variances increase in proportion to the amount of disagreement.

Since ϕ_{ik} is a value averaged over the time interval Δt_u while $\hat{\phi}$ is updated by rate aiding to the end of the time interval, $\hat{\phi}$ is adjusted to make it correspond to near the middle of the interval. This explains the correction term in the equation for the angular difference Θ.

$$\Theta = \phi_m - \hat{\phi} + \left[\frac{\lambda 3}{\lambda_i}\ \dot{\phi}_{DR} + \widehat{\Delta\dot{\phi}}\ \right](0.425)$$

(The subscripts will be dropped for this subsection with the understanding that the equations will be computed for the particular station-base-frequency pairs for which ϕ_{ik} is available in this time slot.)

Computational parameters

Δt_m = 10 seconds

$C = \cos \Theta$

$S = \sin \Theta$

$$\bar{L}_3 = \sigma^2_{\phi\phi} - \sigma^2_{\phi\dot{\phi}}\,\Delta t_m + \sigma^2_{ik}$$

$$L_1 = \frac{\sigma^2_{\phi\phi}\left[\sigma^2_{\phi\phi} + \sigma^2_{ik}\;C\right]}{(\sigma^2_{ik} + \sigma^2_{\phi\phi}\,C)^2 + (\sigma^2_{\phi\phi}\;S)^2}$$

(If $L_1 > 1$ then set $L_1 = 1$)

$$L_2 = \frac{\sigma^2_{\dot{\phi}\dot{\phi}}\;\Delta t_m\left[\sigma^2_{\phi\dot{\phi}}\,\Delta t_m + L_3\;C\right]}{\left[L_3 + \sigma^2_{\phi\dot{\phi}}\Delta t_m\;C\right]^2 + \left[\sigma^2_{\phi\dot{\phi}}\;\Delta t_m\;S\right]^2}$$

(If $L_2 > 2$ then set $L_2 = 2$)

Phase and Phase Rate Error Measurement Update

$$\hat{\phi}\,(k+1) = \hat{\phi}\,(k) + \tan^{-1}\frac{\sigma^2_{\phi\phi}\;S}{\sigma^2_{ik} + \sigma^2_{\phi\phi}\;C}$$

$$\hat{\Delta\dot{\phi}}\,(k+1) = \hat{\Delta\dot{\phi}}(k) + \frac{1}{\Delta tm}\tan^{-1}\frac{\sigma^2_{\phi\dot{\phi}}\;\Delta tm\;S}{L_3 + \sigma^2_{\phi\dot{\phi}}\;\Delta tm\;C}$$

Test: is $\left|\hat{\Delta\dot{\phi}}\right| > 4$ CEC's/SES

Yes. Then set $\hat{\Delta\dot{\phi}} = 0$ and continue

No. Then continue

Variance Measurement Update

These equations must be computed in this order.

$$\sigma^2_{\dot{\phi}\dot{\phi}}(k+1) = \sigma^2_{\dot{\phi}\dot{\phi}}\;(k)\;\frac{L_2^{\,2}}{(\Delta t_m)^2}\left[\sigma^2_{\phi\phi}\;(k) + \sigma^2_{ik}\right] - \frac{2L_2\;\sigma^2_{\phi\dot{\phi}}\;(k)}{\Delta t_m}$$

If $\sigma^2_{\dot{\phi}\dot{\phi}}\;(k+1) > \frac{1}{2\pi^2}$ then set $\sigma^2_{\dot{\phi}\dot{\phi}}\,(k+1) = \frac{1}{2\pi^2}$

$$\sigma^2_{\phi\dot{\phi}}(k+1) = (1-L_1)\left[\sigma^2_{\dot{\phi}\phi}(k) - \frac{L_2}{\Delta t_m}\ \sigma^2_{\phi\phi}(k)\right] + \frac{L_1\ L_2\ \sigma^2_{ik}}{\Delta t_m}$$

$$\sigma^2_{\phi\phi}(k+1) = (1-L_1)^2\ \sigma^2_{\phi\phi}(k) + L_1^2\ \sigma^2_{ik}$$

If $(1 - L_1)^2\ \sigma^2_{\phi\phi}(k+1) > 1\ (\text{cycle})^2$ then set $\sigma^2_{\phi\phi}\ (k+1) = 1$

Test

Is $\sigma^2_{\phi\phi} \leq (3.\ \text{cec})^2$ and $\sigma^2_{\dot{\phi}\dot{\phi}} \leq (0.09\ \text{cec})^2$

Yes: then increment N-counter by +1

No: then reset N-counter to zero

when Measurement Update iterations have been completed then exit.

3.3.10.4 Outputs

Output	Units	Range	Resolution	Destination
$\hat{\phi}_{ik}$	cycles	0-1024	2^{-21}	Combinational Filter Control Indicator
$\sigma^2\phi\phi_{ik}$	cycles^2	0-1	2^{-31}	Combinational Filter Control Indicator
$\sigma^2\dot{\phi}\dot{\phi}_{ik}$	$(\frac{\text{cycles}}{\text{sec}})^2$	$0 - \frac{1}{2\pi^2}$	$\frac{2^{-31}}{2\pi^2}$	Combinational Filter
$\dot{\phi}\ DR_k$	$\frac{\text{cycles}}{\text{sec}}$	$0 - \pm\frac{1}{4\pi}$	$\frac{2^{-31}}{4\pi}$	Combination Filter
N_{Dikj}	counter	0-7	1	Control Indicator Combination Filter

3.3.11 Combinational Kalman Filter

The outputs of the tracking filters are well-filtered values of phase-difference, ϕ, along with the estimates of phase variance, $\sigma^2_{\phi\phi}$, and phase rate variance $\sigma^2_{\dot{\phi}\dot{\phi}}$. It is within the combinational filter operations that the outputs of the tracking filters are statistically, optimally combined, arriving at "best" estimates of system position and velocity. The combinational filter also performs the coordinate conversion from phase difference to geodetic coordinates (latitude and longitude). The rate of change of frequency between the local oscillator in the receiver and transmitted OMEGA signals is also determined. The combinational filter is also used for lane determination. Lane determination (laning) is accomplished by use of a multiple state vector technique.

3.3.11.1 Introduction

a) The combinational filter is a Kalman filter. The Kalman approach to filtering and prediction can be described as a linear, recursive, minimum variance filter. The fundamental concepts involved are those of state, state transition, measurement, and optimal weighting. The states of the filter are differentials of system parameters; i.e., error in position, error in velocity, etc. The states of the system are described by the solution of linear vector difference equations. The equations upon which filter operations are predicated are:

1) $X(K) = \phi\ (K, K-1)\ X\ (K-1) + V(K)$

2) $Y(K) = M(K)\ X\ (K) + U(K)$

where X(K) is the vector state of the system error (Table 3.3-1)

3) $\phi(K, K-1)$ The transition matrix.

4) V(K) system forcing function (for Kalman operations a white noise sequence)

5) Y(K) A vector of state observables (measurement)

6) M(K) A state transformation matrices (Extraction matrix)

7) U(K) Measurement noise (white noise sequence)

TABLE 3.3-1 STATE VECTOR ELEMENT MEANING

Element Number	Symbol	Meaning	Comments
1	$-\delta_{\theta 3}$	Position Error along the -R2 direction of R_{ij} matrix	
2	$\delta_{\theta 2}$	Position Error along the -R3 direction of the R_{ij} matrix	
3	t_o	Time difference between the transmitting station phase and the receiver oscillator phase	Not Used
4	$\dot{t}_o$	Time rate of change of t_o	
5	P_1	Propagation Parameters	Not Used
6	P_2		
7	P_3		
8	V_2	Error in East component of velocity which is error along the R2 direction of the R_{ij} matrix	
9	V_3	Error in North component of velocity which is error along the R3 direction of the R_{ij} matrix	

b) The Kalman technique linearly combines the previous estimate X with the measurement to arrive at a minimum variance estimate which is then time updated until the next measurement. The measurement operation is best described by:

$$\hat{X}(K/K) = \hat{X}(K/K-1) + b(K) \left[Y(K) - M(K)\,\hat{X}\,(K/K-1)\right]$$

where: X(K/K) new estimate of state at time K based on K measurements

X(K/K-1) Time updated prediction of previous estimate at time K based on K-1 measurements

b(K) optimal weighting vector

Optimal weighting is determined by means of recursive techniques based upon obtaining minimum error variances. This weighting is a function of the covariance of the difference between system error state and estimation of state; i.e.:

$$P = E\left[(X-\hat{X}) \quad (X-\hat{X})^T\right]$$

The combinational filter is, therefore, capable of computing optimal estimates of position and velocity along with other elements of its state vector. The filter utilizes two types of observations. One is the difference between the phase difference of the tracking filter and a value of phase difference based upon the combinational filter's time-updated position. The other observation consists of a received correction to position entered through the C & I Panel. Based on these measurements, the filter computes optimal estimates of: position errors, driving velocity errors, and oscillator drift. The recursive formulation of filter operations permits each measurement to be processed and then discarded. In this fashion the values of previous measurements do not have to be stored in the computer, since all the information is contained within the state estimate vector and covariance matrix.

c) The uncertainty in position error can produce an ambiguity in lane count, the number of wave lengths between the transmitting station and the receiver. This ambiguity exists primarily when the system is first turned on. To resolve this lane ambiguity, a multiplicity of state vector estimates X_ℓ is carried by the filter. These X_ℓ correspond to the several possible lanes or integral values of phase measurement. As measurements corresponding to the three different frequencies are taken the ambiguity in lane count is reduced. Measurements from different stations tend to further reduce the lane uncertainty. The overall effect is a reduction in the number of state

vector estimates X_ℓ that can be considered reasonable estimates of the true state vector until only one reasonable estimate remains. The criterion for reasonableness is based upon variance considerations. An average of the X_ℓ, X_{AVG}, is also computed.

d) Interfacing requirements with other routines have been touched upon above. A restatement and summary will aid in clarification of the operations performed. The routines that will interface with the combinational filter include:

1) Navigation and Velocity Processing/Mode Select

2) Base Station Selection

3) Propagation

4) Tracking Filter

5) C & I

The interfacing with the first two routines includes mode corrections to system position, and corrected system velocities. Interfacing with the last routine, in addition to display functions, includes position correction measurement residual data. The tracking filter supplies ϕ, $\sigma^2_{\phi\phi}$ and $\sigma^2_{\dot{\phi}\dot{\phi}}$ for a particular station/frequency. Knowledge of combinational filter utilizations and resetting of tracker filter parameters is required for this particular interface. The interfacing with the propagation routine includes the C element and ϕ corrections for the particular station/frequency.

e) The error vector has a rank of nine to allow for the possible error sources in various OMEGA mechanization. In the phase difference approach five of the nine elements are utilized.

f) The estimates described above are treated computationally in the combinational filter as elements of a vector (= error state estimate vector = state vector = estimator = X).

g) Before the intra-cycle operations are described mathematically, the vectors and matrices which are required to carry out these operations will be defined.

1) State vector (X: 9 x 1)

2) Transition matrix (Φ: 9 x 9)

3) Covariance matrix (P: 9 x 9, symetric and positive semidefinite)

4) System Noise Matrix (R: 9 x 9 and diagonal)

5) Measurement (Y: 1 x 1)

6) Measurement Matrix (M: 1 x 9)

7) Measurement Noise (C: 1 x 1)

8) Measurement-residual (Res: 1 x 1)

9) Measurement-residual variance (V: 1 x 1)

10) Optimum weighting vector (b: 9 x 1)

11) Epsilon (ϵ : 1 x 1)

h) Using the definitions above, there are six distinct operations required of this routine. These operations are:

1) Estimation/covariance matrix time-update

2) Measurement generation

3) Estimator/covariance matrix measurement update

4) Estimator and System Control

5) Initiatization

6) Multiple State Vector Modifications

3.3.11.1.1 <u>Estimation/Covariance Matrix Time-Update:</u>

a) The operations consist of time update of the X and P matrices. The equations utilized are:

1) $\hat{X} = \Phi\hat{X}$

2) $P = \Phi P \Phi^T + R$

b) Both these equations require the use of the transition matrix Φ which mathematically propagates errors across the time interval since the last update. The transition matrix is shown in Table 3.3-2.

c) The transition matrix provides only the propagation of predictable (i.e., deterministic) elements of X and P across the computational interval Δt_u. Propagation of the random effects across this interval is accomplished by means of the additive diagonal matrix R. Table 3.3-3 specifies the diagonal elements of R by navigation mode.

TABLE 3.3-2 TRANSITION MATRIX

	$-\delta\theta_3$	$\delta\theta_2$	t_o	$\dot{t}_o$	P_1	P_2	P_3	δV_2	δV_3
$-\delta\theta_3$	1							$\frac{\Delta t}{R_o}$	
$\delta\theta_2$		1							$\frac{\Delta t}{R_o}$
t_o			1	12 Δt					
$\dot{t}_o$				1					
P_1					0				
P_2						0			
P_3							0		
δV_2								$1-\beta_V\Delta t$	
δV_3									$1-\beta_V\Delta t$

TABLE 3.3-3 SYSTEM NOISE MATRIX

ELEMENT NO.	EXPRESSION
(1, 1)	0
(2, 2)	0
(3, 3)	0
(4, 4)	0
(5, 5)	0
(6, 6)	0
(7, 7)	0
(8, 8)	$2\sigma^2_{NAV}\beta_{\Delta V}\Delta t$
(9, 9)	$2\sigma^2_{NAV}\beta_{\Delta V}\Delta t$

NOTE: All off-diagonal terms are zero.

d) Investigation of the elements in Φ and R reveals the dependence of time between updates as a factor in computation. This update should be done at a constant rate to minimize computational cost. Due to the dynamical errors associated with maneuver and the utilization of velocity error elements as output information, it is felt that this iteration time should be a maximum of 30 seconds. The iteration time chosen is the natural one of 10 seconds.

3.3.11.1.2 Measurement Generation:

a) There are two measurement types available and, therefore, generated prior to measurement update. They are: 1) Tracking filter estimate of the phase of a station/frequency combination, and 2) Navigator inserted position correction. For the first type, the measurement is utilized for estimation of the entire system error model while the second type is utilized for resetting of position error in accordance with navigator indication of quality fix. For each measurement type, however, the operations are similar and consist of generation of the measurement residual, Res_i, extraction matrix, M_i and measurement confidence scalar, C_i.

b) The tracking filter measurements occur at an asynchronous rate. Availability of a measurement is indicated by the n counter of the tracking filter, as described in paragraph 3.3.10.

c) When a tracking filter measurement for some phase-difference pair is accepted, an estimate of that measurement is computed. This computed estimate is based upon the present position as indicated by the Navigation Routine and propagation corrections determined by the Propagation Routine. The measurement Y_i is the difference between this computed phase estimate and the phase estimate from the tracking filter. For each measurement, the measurement residual is computed. The measurement residual is the difference between the measurement Y_i and its predicted value $M_i\hat{X}$. The measurement matrix M_i consists of the algebraic relationships between the measurement and the error state $\hat{X}$. The elements of M_i are computed within this routine. The remaining parameter, measurement noise, is an addition of $\sigma^2_{\phi\phi}$ and the confidence figure from the propagation routine associated with its computations. After the time-update of the state vector and the covariance matrix, the tracking filter outputs are scanned station-pair by station-pair, starting with the station-pair immediately following the last used by the combinational filter. As mentioned previously a tracking filter output is ready to be processed by criteria explained in paragraph 3.3.10. When a station is processed, all frequencies meeting the readiness criteria are processed sequentially. When a tracking filter has been read, the combinational filter resets the tracking filter variances to their velocity-mode-dependent initial values. If no tracking filters are ready for use by the combinational filter, the routine exits.

d) The position correction measurements residual is supplied through the panel and Panel Routine, and relates thru M_i to the positional error parameters only. The extraction matrix elements are, therefore, computed within this routine. The measurement corruption noise is a function of navigator choice from a set of three position insert accuracies (0.5 mi., 5 mi., 20 mi.).

3.3.11.1.3 Estimator/Covariance Matrix Measurement-Update (Estimation):

a) The estimation operation involves a linear, unbiased weighting of the measurement residual, Res_i, with the current estimate X of the error states, to form a new, minimum-variance error estimate. This operation is expressed by

$$\hat{X} = \hat{X} + b_i \, Res_i$$

Generation of the optimum weighting vector, b_i, requires three expressions. These are: 1) the predicted measurement variance $M_i \, P \, M^T{}_i$, 2) measurement corruption, or confidence, variance C_i and 3) the divergence control factor ϵ. The matrix P which is used to generate $M_i P M^T$ for the first measurement residual during a measurement update is that which resulted from the time-update operation on $\hat{X}$ and P.

b) Similarly, whenever the estimation is measurement updated, P is also correspondingly updated to reflect the reduction in the uncertainty associated with the new estimate.

Because of the utilization of fixed point limited word length arithmetic for all internal computations, an epsilon factor, ϵ , is specified to prevent divergence of the estimation process. This divergence can result from the buildup of arithmetic round-off and truncation errors leading to loss of positive semidefiniteness of P. An additional use of the epsilon factor is to reduce mismodeling effects.

3.3.11.1.4 Estimator and System Control:

The position errors estimated by the state vector are used for system control. The present position estimate as carried in the Navigation Routine is corrected after every time update by the position errors estimated in the state vector. The position error state vector elements are then reset to zero. The velocity errors estimated by the state vector are also used for control. They are used to update the corrected velocity used in the navigation routine. The oscillator parameter element is used to control the computed burst pattern start times.

3.3.11.1.5 Initialization:

Initialization occurs after synchronization and whenever the initial time or position is entered by the operator if the entry occurs after synchronization. Initialization consists of setting:

a) State vector = 0.

b) Covariance matrix = 0.

c) $P_{11} = P_{22}$ = inserted position quality if position has been entered.

P_{11} and P_{22} are set equal to the values existing when the system was turned off.

P_{11} and P_{22} are set equal to a position quality of (0.5 n mi) if time has been entered and position has not been entered.

d) P_{44} = (0.25 microsec/microsec)^2.

e) σ^2_{kick} = (5 n mi)^2 or P_{11}, whichever is largest.

3.3.11.1.6 Multiple State Vector Modifications:

a) Thus far the operational description has been written as though only one state vector estimate $\hat{X}$ existed. During most of the cruise this will be the case. However, until the correct lane has been determined there will be a multiplicity of state vector estimates. Under these conditions the time update equation for the $\hat{X}$ must be cycled through all the state vectors.

$\hat{X}_j = \Phi \hat{X}_j$ All available j

The time update equation for the covariance matrix is cycled just once, as there is only one covariance matrix regardless of the number of state vector estimates.

b) The measurement update equation is cycled once for each reasonable state vector estimate generated as a result of the measurement and the previous vectors.

$\hat{X}_j = \hat{X}_j + b\ res_j$ All reasonable j

A reasonable state vector is one which passes a confidence criterion given by

$[Res_j]^2 < 9\ [MPM^T + C] + (4\ CEC)^2$

This reasonableness test essentially means that the residual for that state vector is within 3 standard deviations of the expected value.

c) The measurement update equation for the covariance matrix is computed just once, provided at least one reasonable state vector exists.

If conditions should happen to be such that no reasonable state vector is generated by the measurement (misfire), then one of several courses of action is pursued. If the reasonableness criterion was less than (15 cec)^2, then (15 cec)^2 is added to the criterion and the procedure is tried again. If the reasonableness criterion exceed (15 cec)^2, then the procedure depends upon the assumed validity of the measurement.

If the phase rate error variance $\sigma^2_{\dot{\phi}\dot{\phi}}$ does not exceed (0.00031 cycles/sec)^2 the failure to pass the reasonableness criterion means that either 1) the present estimate of position is incorrect, or 2) the measurement is incorrect due to some other reason. In either case the filter is "opened up" by setting the two position variances to the larger value between their present value and the value at sigma squared kick (σ^2kick). The present measurement is disregarded and the filter then takes the next station pair. The misfire count is incremental to record this occurence. If $\sigma^2_{\dot{\phi}\dot{\phi}}$ is greater than (0.00031 cycles/sec)^2 this particular measurement is disregarded but the filter will examine the other frequencies from this station pair if they are available.

d) An additional constraint on the station selection scheme exists when the variance on position error as carried in the covariance matrix exceeds 4 n miles squared $[P_{11} + P_{22} > (4 \text{ n miles})^2]$. When this occurs, two frequencies from a given station must be available for processing. This constraint holds down the number of extraneous state vectors generated when a large uncertainty in position exists. A measurement generated under these conditions consists of the difference of the measurements (Y_i) of the two frequencies. The measurement matrix (M) also is computed by differencing the M_i for the two frequencies. Thus only one measurement is generated from the two tracking filter outputs.

3.3.11.2 Inputs

a) The following inputs are from the tracking filters. The input timing will depend upon the availability of tracking filters; i.e., those which satisfy the readiness criterion (see 3.3.10). The combinational filter will process one station-base pair on all frequencies once every 10 seconds. Thus if four station-base (or base-base) tracking filters were available there would be one which must wait 40 seconds before it would be processed by the combinational filters.

Input	Units	Range	Resolution	Origin
$\hat{\phi}_{ik}$	Cycles	0-1024	2^{-21}	Combinational Filter
$\sigma^2_{\phi\phi_{ik}}$	$Cycles^2$	0-1	2^{-31}	" "
$\sigma^2_{\dot{\phi}\dot{\phi}ik}$	$\left(\frac{Cycles}{Sec}\right)^2$	$0-\frac{1}{2\pi^2}$	$\frac{2^{-31}}{2\pi^2}$	" "
$\dot{\phi}_{DR\ k}$	$\frac{Cycles}{Sec}$	$0-\pm\frac{1}{4\pi}$	$\frac{2^{-31}}{4\pi}$	" "

b) The following inputs are from the Propagation Prediction Processing (Paragraph 3.3.12). They are furnished as needed per each tracking filter input noted above.

Input	Units	Range	Resolution	Origin
θ_2	Cycles	0-±32	2^{-10}	Propagation Prediction
θ_3	Cycles	0-±32	2^{-10}	" "
σ^2_{ppi}	$Cycles^2$	0-1	2^{-31}	" "

c) Inputs from navigation and velocity processing include the following:

$\left[R_{ij}\right]$ System Position Matrix at start of Kalman update.

θ_p System heading angle measured N to the R_3 vector CCW position.

NAVMODE Marker designating Log or Pseudo navigation mode.

Input	Units	Range	Resolution	Origin
r_{ij}	None	$\lvert X \rvert \leq 1$	2^{-30}	Navigation
θ_p	Cycles	0-±1/2	2^{-32}	"
NAV MODE	Marker	---	---	"

d) Inputs from C&I panel/routines

δP_N, δP_E Position Error corrections North and East.

STAT MRK_i Defines which stations will be used for measurement

COLD START MKR Indicates restart procedures

C_{pos} Noise variance for position measurement (three values for 0.5, 5.0 and 20 n miles)

Input	Units	Range	Resolution	Origin
δP_N, δP_E	Ft	$0\text{-}6x10^6$	1	C-I Panel Routines
STAT MRK_i	Marker	A,B,...,H	---	C-I Input
COLD START	"	---	---	C-I Panel Routines
C_{pos_i}	$Cycles^2$	0.006944.. 0.06944... 0.277....		C-I Panel Routines

e) From Base Station Selection (Paragraph 3.3.8)

BASE Defines which station is currently designated as the base station.

3.3.11.3 Mechanization Equations

The following lists the equations to be mechanized and provides the order of operations to be performed and the logical decisions to be made.

3.3.11.3.1 Equations:

a) Time Update

Time propagation of state (X) and covariance matrix (P).

Compute Φ (K, K-1)
(Refer to Table 2, transition matrix)

$\hat{X}$ update

$\hat{X}_k$ (K) = ϕ(K, K-1) $\hat{X}_k$ (K-1)   All available $\hat{X}_k$

P update

$$P(K) = \Phi(K, K-1)\ P(K-1)\ \Phi(K, K-1)^T + R(K)$$

The system is considered ambiguous if the uncertainty in position exceeds 4 n miles $\left[P_{11} + P_{22} > (4 \text{ n mi})^2\right]$. The mode-dependent expressions for the transition matrix are detailed in Table 3.3-2. The system noise matrix R is given in Table 3.3-3.

$$\text{Time increase} = \int_0^{t_\bullet} t_o \, dt$$

b) Measurement Generation

1) The routine branches depending upon whether the measurement is from the tracking filter outputs or from a navigator inserted position. For the latter the quantity Y_i is computed in the C and I Routine, M_i is computed in this routine as given in Table 3.3-4b and

$C_i = \sigma^2$ (δ Position insert); C_{pos_i} from C-I.

i = 0.5, 5.0 or 20.0 n mile position insert as chosen by the navigator

For tracking filter measurements the routine branches to the station select scheme which has been described in the operational description. If an acceptable tracking filter measurement is not available the routine exits. If a measurement is available it is tested to see if it is a "good measurement". For a good measurement

$$\sigma^2_{\ddot{\phi}\ddot{\phi}} < (0.00031 \text{ cycles/sec})^2$$

This quality rating of the measurement is used only if no state vectors are generated by the measurement.

2) The earth central angle between the present position and both the transmitting station and the base station for the tracking filter being processed is generated in this routine by the following equations:

TABLE 3.3-4 MEASUREMENT (EXTRACTION) MATRICES

a) Tracking Filter Measurement

$$
\begin{array}{ccccccccc}
\left[\dfrac{R_o \sum_{j=1}^{3} r_{2j} s_j}{\lambda_k \sin \phi_D}\right. & \dfrac{R_o \sum_{j=1}^{3} r_{3j} s_j}{\lambda_k \sin \phi_D} & \dfrac{V_L}{\lambda_k} & \begin{array}{c} 10 \times^{**} \\ \text{(freq.)} \end{array} & M_{p1}{}^* & M_{p2}{}^* & M_{p3}{}^* & 0 & \left.0\right] \\
\text{STATE: } -\delta\theta_3 & \delta\theta_2 & t_o & \dot{t}_o & P_1 & P_2 & P_3 & \delta V_2 & \delta V_3
\end{array}
$$

$$\phi_D = \cos^{-1}\left\{\sum_{j=1}^{3} r_{1j} s_j\right\}$$

k = 1, 2, 3 (OMEGA frequency)

*Generated in Propagation Prediction Routine, but not currently mechanized in KALMAN; i.e., $M_{pi} = 0$.

**This element is zero unless it is a Base-Base Measurement.

b) Positional Correction Insert (Generated in C & I Computational Routine)

$$
\begin{array}{l}
\delta P_E^* \\
\left[\begin{array}{c|c|c|c|c|c|c|c|c} \cos\theta_P & -\sin\theta_P & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{array}\right] \\
\delta P_N^* \\
\left[\begin{array}{c|c|c|c|c|c|c|c|c} \sin\theta_P & \cos\theta_P & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{array}\right]
\end{array}
$$

$\delta P_E / \delta P_N$ is positive when the computed position is to the East/North of the inserted position.

$$r_{11} = r_{11} \frac{(\text{earth's polar radius})^2}{(\text{earth's equatorial radius})^2}$$

$$\theta_1 = \tan^{-1} \frac{\left|\vec{R}_1 \times \vec{S}\right|}{\vec{R}_1 \cdot \vec{S}} = \tan^{-1} \frac{\sqrt{(\vec{R}_1 \times \vec{S}) \cdot (\vec{R}_1 \times \vec{S})}}{\vec{R}_1 \cdot \vec{S}_1}$$

$$= \tan^{-1} \frac{\left[(r_{12}s_3 - r_{13}s_2)^2 + (r_{13}s_1 - r_{11}s_3)^2 + (r_{11}s_2 - r_{12}s_1)^2\right]^{\frac{1}{2}}}{r_{11}s_1 + r_{12}s_2 + r_{13}s_3}$$

The components of the transmitter location vectors (station and base) S must be in geocentric (not geodetic) coordinates. The vector $\vec{R}_1$ is the first row of the R_{ij} Matrix modified by the first equation to change $\vec{R}_1$ from geodetic to geocentric coordinates.

3) The propagation routine computes two other pairs of angular quantities: θ_2, the earth speroidal correction angle, and θ_3, the propagation correction angle based upon the propagation conditions assumed to exist for the particular path and time. Again, this will be done for both the station and the base of the designated pair. The sum $\theta_1 + \theta_2 + \theta_3$ is converted to phase angle and represents the computed phase measurement between the submarine and one transmitter. Two such values must be differenced as will be indicated. Also, unless otherwise noted, all calculations are done on the same frequency.

The following will apply to subscripts:

C indicates a computed value (not an input value)

i indicates a station; i includes all stations

k indicates a base; k is fixed until the base station is redesignated (see 3.3.8).

When there is a difference in calculations for i = k it will be so noted.

$$\phi_{Ci} = \frac{R_o}{\lambda} (\theta_1 + \theta_2 + \theta_3)_i$$

R_o is earth's equatorial radius

λ is wavelength of the particular frequency

3) The propagation routine computes an estimate of the variance of each ϕ_{Ci}, designated σ^2_{ppi}.

The measurement Y_{ik}, and its variance C_{ik}, are then computed along with the epsilon factor. These measurements vary slightly depending upon whether it is a station-to-base or a base-to-base calculation.

In the following it will be noted that the subscript k has been deleted from the measurement notation; i.e., Y_i instead of Y_{ik}. Here, as in calculations that follow, the variable subscripted i will denote station-to-base relationships when $i \neq k$, or base-to-base relationships when $i = k$. Subscript k will apply to base-to-base relationships only.

$$\text{set} \quad \phi'_{Ci} = \phi_{Ci} - \phi_{Ck} + (t_i - t_k)\ \frac{\hat{\phi}_k}{10} \qquad i \neq k$$

$$\text{or} \quad \phi'_{Ck} = 10\,\dot{\phi}_{DRk}$$

Now ϕ'_{Ci} is a function of θ_1, θ_2 and θ_3 evaluated at some time after burst reception of station i. $\frac{\hat{\phi}_k}{10}$ is the phase rate in radians/sec of the submarine with respect to the base station and t_i, t_k the difference in time between station and base reception. Consequently, the last term in the equation time-adjusts the prediction of ϕ_{Cik} to be compatible with that time at which the measurement was taken.

$$Y_i = \hat{\phi}_{ik} - \phi'_{Ci} \qquad \text{all } i$$

The M matrix for base-to-base calculations becomes:

$$M_k = \begin{bmatrix} 0 & 0 & 0 & 10(j) & 0 & 0 & 0 & 0 & 0 \end{bmatrix}; \qquad j \text{ represents frequency}$$

For both 1) and 2) above the following variance and epsilon calculations apply:

$$C_i = \sigma^2_{\phi\phi i} + \sigma^2_{ppi}$$

$$\text{Where } \sigma^2_{ppi} = \sigma^2_{ppik} + \sigma^2_{ppkk} \qquad \text{for } i \neq k$$

$$C_k = \sigma^2_{\phi\phi k} \qquad i = k$$

$$\epsilon = \frac{1}{16} C_i \quad \text{or} \quad \frac{1}{16} C_k$$

4) As explained in the operational description, a slightly different procedure is followed if the variance on position error as carried in the covariance matrix exceeds 4 n miles squared. $\left[P_{11} + P_{22} > (4 \text{ miles})^2\right]$. For this case two acceptable tracking filters must be present from a given station-base pair (corresponding to two transmission frequencies). The two tracking filter outputs are processed sequentially up to the point thus discussed. The M matrix and the observation Y are formed by differencing the ones computed for each frequency. The quantity C is computed by summing both propagation variances and both tracking filter variances as the equations in 1) above indicate. The change in the M matrix is designated as:

$$M_i = M_{ij_1} - M_{ij_2}$$

5) At this point the same computations are performed for all cases.

$$Q_i\ (K) = M_i\ P(K)\ M_i^T + C_i$$

$$b_i = \left[PM_i^T + M_i^T\epsilon\right]\ \left[Q^{-1}\right]$$

$$KQ_i = 9Q_i + (4\ \text{CEC})^2;\ \text{(Tracking Filter Operation)}$$

or

$$KQ_i = 9Q + (2\ \text{n miles})^2;\ \text{(Position Fix)}$$

b_i is the Kalman weighting matrix and KQ is the confidence criterion to be used in generating new state vectors.

The value of KQ is now compared with KQ_{MAX} whose value depends upon the variance value of $P_{11} + P_{22}$ and the measurement frequency

$P_{11} + P_{22} < (4\ \text{n miles})^2$?

Yes: Set $KQ_{MAX} = L_\lambda^2 + 0.75$

No: Then operational mode is difference frequency and

$$KQ_{MAX} = (L_{\lambda_1} - L_{\lambda_2})^2 + 0.75$$

Where L_λ is the number of phase difference lanes in 36 n miles.

Set POS UNC marker to Control-Indicator

Is $KQ < KQ_{MAX}$?

Yes: Use KQ and continue.

No: Set KQ equal to appropriate KQ_{MAX} (above) and continue.

6) The following outlines the development of new state vectors, the computation of the average state vector, and the covariance matrix generation after the measurement. The residual is computed:

$$Res_{ik} = Y_i - M_i \hat{X}_k$$

The residual combines the observation with each available state vector in turn. The residual is then checked to see if it is reasonable:

$$\left| Res_{ik} \right| < KQ_i$$

If the test is successful (the residual is reasonable) a new state vector is computed:

$$\hat{X}_k = \hat{X}_k + b_i \; Res_{ik}$$

The residual is also incremented (and decremented) by integer (one lane) values and tested again for reasonableness. New state vectors are computed if the criterion is passed. This incrementing (decrementing) continues until the reasonableness test is failed. Thus several new state vectors could be generated from a single previous state vector. It is also possible that $\hat{X}_k$ may generate no new state vectors. Once the system has lane resolved, it is expected that only one state vector will be generated.

The OMEGA Ambiguity marker, ΩAMB, is set if more than one state vector exists.

7) Once a new state vector is generated, several tests are performed to determine its validity. Because of laning considerations, state vectors with position errors of more than ± 36 miles are considered unreasonable. A state vector is also tested to see if it is "nearly the same" as a previously generated state vector. Two state vectors are defined to be "nearly the same" if the first three elements of the state vector are identical with the exception of the last three bits. This test avoids generation of state vectors which cannot be resolved.

c) Average State Vector Computation

The combinational filter generates new state vectors based upon the values of the residuals computed for a given tracking filter output (corresponding to a given station difference and frequency pair). An average state vector is also computed by computing an element-by-element average over the state vectors generated:

$$\hat{X}_{avg} = \hat{X}_{avg} + \frac{\hat{X}_k - \hat{X}_{avg}}{\#\text{ of state vectors}}$$

For practical reasons of computer storage, the state vectors generated are not stored in their entirety. The first four elements (corresponding to position error t_o and t_o) are stored for each vector. The remaining five elements for each vector are taken to be those of X_{avg}.

d) Covariance Matrix Generation

If any new state vectors are generated by a measurement, a measurement updated covariance matrix is computed:

$$P(K) = P(K) - b_i M_i P(K) + \epsilon M_i^T b_i^T$$

If no new state vectors are generated by a measurement, the covariance matrix is not measurement updated.

3.3.11.3.2 <u>Glossary of Terms</u>:

Symbol	Meaning
$\hat{X}$	Error state estimate vector
$\hat{X}(i)(i=1\rightarrow 9)$	Elements of $\hat{X}$, mode dependent
P	Covariance matrix
$P(i,j)(i,j=1\rightarrow 9)$	Elements of P
R	System noise matrix
$R(i,i)(i=1\rightarrow 9)$	Diagonal element of R
Φ	Transition matrix
$\Phi(i, j)(i, j=1\rightarrow 9)$	Elements of Φ, mode dependent
Y_i $(i = 1\rightarrow 8)$	Measurement from station pair i
Res_{ik}	Residual using measurement Y_i and state vector estimate k.
M_i	Measurement (Extraction matrix) for Y_i
C_i	i^{th} measurement variance (scalar) from C-I or TF + Prop. Predict
ϵ	Divergence control factor
b_i	Weighting factor for Y_i
$\overrightarrow{R_1}$	First row of R_{ij} matrix
r_{ij}	Element of R_{ij} matrix
$\overrightarrow{S_i}$	Positional vector of i^{th} station in earth-fixed coordinates
s_i	Element of $\overrightarrow{S_i}$
R_o	Equatorial earth radius

Symbol	Meaning
$\lambda_i (i=1, 2, 3)$	Wavelength of OMEGA signal (10.2 kHz, 11.33 kHz, 13.6 kHz)
ΔT	Time between time updates
θ_P	WANDER AXIMUTH ANGLE positive CCW from NORTH to R_3 AXIS
V_L	Average propagation velocity of OMEGA signals (chart value)
$\hat{\phi}_{ij}$ $(i=1\rightarrow 8, j=1\rightarrow 3)$	TRACKING FILTER phase estimate of station/frequency signal
$\phi_{Cij} (i=1\rightarrow 8, j=1\rightarrow 3)$	Computed expected phase for STATION/frequency signal
$\sigma^2_{\phi\phi_{ij}} (i=1\rightarrow 8, j=1\rightarrow 3)$	TRACKING FILTER ESTIMATE OF VARIANCE of $\hat{\phi}_{ij}$
$\sigma^2_{pp_{ij}} (i=1\rightarrow 8, j=1\rightarrow 3)$	Propagation prediction estimate of confidence in ϕ_{Cij}
δP_n	Panel inserted positioned connection, northerly direction
δP_E	Panel inserted positioned correction, easterly direction.

3.3.11.3.3 <u>Statistical Constants</u>:

Symbol	Description	Units	Value
$\sigma_{\delta\theta_i}(0)$	Initial position standard deviation for both $\delta\theta_2$ and $\delta\theta_3$ i = 1, 2, 3 elements P(1, 1) and P(2, 2)	nautical miles	0.5 5.0 20.0
$\sigma_{t_0}(0)$	Initial standard deviation crystal phase offset, element P(3, 3)	seconds	255×10^{-6}
$\sigma_{\dot{t}_o}(o)$	Initial standard deviation of crystal phase-drift, element P(4, 4)	seconds/second	0.25×10^{-6}
$\sigma_{pi}(0)$	Initial standard deviation of propagation error states i = 1, 2, 3 elements P(5,5), P(6,6), P(7,7)	-	0.1
$\sigma_{MAN}(0)$	Initial standard deviation of δV_2 and δV_3 for Manual Velocity mode elements P(8,8) and P(9,9)	knots	10
$\sigma_{LOG}(0)$	Initial standard deviation of δV_2 and δV_3 for LOG mode elements P(8,8) and P(9,9)	knots	3

Symbol	Description	Units	Value
σ (δ Pos Insert)$_i$	Confidence standard deviation of inserted position measurement variance i = A,B,C	Nautical miles	0.5 5.0 20.0
β_{Pi}	Inverse correlation time of propagation error states i = 1,2,3	$\frac{1}{\text{hours}}$	$\frac{1}{.5}$
β_I	Inverse correlation time of δV_2 and δV_3 for Manual Velocity Mode	$\frac{1}{\text{hours}}$	$\frac{1}{0.05}$
β_{LOG}	Inverse correlation time of δV_2 and δV_3 for ship's log mode	$\frac{1}{\text{hours}}$	$\frac{1}{0.05}$

3.3.11.4 Outputs

Symbol	Meaning
$\delta\theta_2$, $\delta\theta_3$	Kalman rotation corrections to the $\left[R_{ij}\right]$ matrix in Navigation and Velocity processing
δV_2, δV_3	Velocity corrections to V_2 and V_3 in Navigation and Velocity processing.
$NCTR_{ikj}$	Number of measurements taken from each tracking filter.
POS UNC	Marker to Control-Indicator which informs operator of a position uncertainty and that combinational filter has entered different frequency mode.
ΩAMB	Marker to Control-Indicator indicating more than one state vector exists.
P_{11}, P_{22}	Radial position errors contained in the P matrix. Available for Control-Indicator display.
TIME INCREMENT	Integrated value of crystal drift for sync. time control.

Output	Units	Range	Resolution	Destination
$\delta\theta_2$, $\delta\theta_3$	radians	$\|x\| \leq \pi$	2^{-31}	Navigation
δV_2, δV_3	ft/sec	$\|x\| < 4096$	0.125	Velocity & Heading Processing
$NCTR_{ikj}$	Counts	0-99	--	Control-Indicator
POS UNC	Marker	--	--	Control-Indicator
ΩAMB	Marker	--	--	Control-Indicator
P_{ii}	$radians^2$	$0-(2\pi)^2$	$2^{-15}\pi$	Control-Indicator
TIME INCREMENT	seconds	$\|x\| \leq 0.005$	10^{-9}	Executive
PANEL COUNT	counts	--	--	Control-Indicator

3.3.12 Propagation Prediction

3.3.12.1 Introduction

In order to successfully determine the current submarine position from the phase information received, it is necessary to know the phase velocity of the incoming wave along the path, and the path length. To obtain a more accurate estimate of submarine position, we will investigate a number of effects (magnetic, day/night (diurnal), ground conductivity, and variations in radius of the earth) that cause position to deviate from that calculated using constant velocity over an assumed perfect sphere.

Operation of the OMEGA Navigation System is based on the measurement of the phase of several transmitters operating in the 10-14 kHz electromagnetic spectrum. It has been established that the eight proposed OMEGA transmitters will cover the earth with signal levels adequate to permit that phase measurement. Furthermore, it is generally accepted that signals in this spectrum propagate through a waveguide made up of two concentric spheres; one sphere is the earth, the other is the ionosphere.

Under ideal conditions a simple phase measurement would suffice to precisely locate a receiving station. However, the walls of the waveguide are not perfect and are affected by several parameters, specifically the effect of the sun on the ionosphere; earth's magnetic field; ground conductivity, and others. These imperfections in the waveguide walls cause changes in the propagation of the electromagnetic signal, the phase velocity, which reduce the accuracy of the phase measurement.

The phase velocity of such waves in a perfect waveguide with this geometry has been found to depend on the width of the waveguide (the height of the ionosphere) and on the electrical conductivity of the surfaces. The electric conductivity of the earth's surface is important, as well as that of ionosphere. In the case of the ionosphere, the problem is complicated theoretically because a continuous wall does not exist; rather, the electron density and collision frequency vary with height in some manner which can be approximated as exponential. The effect of the earth's magnetic field on the phase velocity must also be considered. This has been analyzed theoretically and the assymetry between propagation from east to west and from west to east has been observed.

These factors, along with one to account for the oblateness of the earth, are incorporated into a computer program designed to provide incremental real-time corrections along the propagation path.

3.3.12.2 Inputs

Input	Units	Range	Resolution	Origin
Date/Time	Days	0-2043	1 Minute	Control-Indicator I/O
$[R_{ij}]$	None	$\lvert r_{ij} \rvert \leq 1$	2^{-31}	Navigation

3.3.12.3 Processing

The propagation predictions are made for each frequency and each transmitter, giving up to (3) x (8) = 24 sets of calculations. First the operations that apply to the entire path and hold for all three frequencies are performed for each station. Then calculations that are frequency related are made.

3.3.12.3.1 Date-Time: The number of days since Jan 0.0 of 1968 is calculated, to be used in determining the sun position, and from that the daylight portion of the propagation path.

This can be accomplished by determining the number of days in prior years, looking up in a table the number of days in the months preceding the current one, and adding these to the number of days already past in the current month, plus the fractional part of the current day.

Current Month	M	(Jan = 1, Dec = 12)	Dm	(Days in prior months, since Jan 1.)
Jan 31	1		0	
Feb 28	2		31	
Mar 31	3		59	
Apr 30	4		90	
May 31	5		120	
Jun 30	6		151	
Jul 31	7		181	
Aug 31	8		212	
Sep 30	9		243	
Oct 31	10		273	
Nov 30	11		304	
Dec 31	12		334	

D = Number of days since Jan 0.0, 1968

D = 365 (year - 68) + Dm + (Number of days in current month) + LEAP

(Last two digits)(From table above)

$$+ \frac{(3600)\ (hrs) + (60)\ (min) + secs}{86400} \quad \text{(fraction of present day)}$$

where LEAP = number of Feb 29 days between Jan 1, 1968 and present.

A seasonal index, IS, is also determined, to be used in estimating the diurnal effect.

IS is an integer, 1 to 24, that tells which two-week period of the year the current date-time falls into.

That is, IS is the integer part of:

$$\left[\frac{D}{15.2184} + 1.0\right] \text{ modulo } 24$$

where $\frac{365.2416}{24} = 15.2184$

3.3.12.3.2 <u>Sun Vector</u>:

Compute:

E = (D + 0.5), modulo 1

i.e., E is the fractional part of (D + 0.5)

$L_s = K_1 D + K_2$

$K_1 = 0.0172027914$

$K_2 = 4.8632700$ (L_s on Jan 1, 1972)

NOTE: K_2 is subject to update to current year

L_s is called the "longitude of the sun"

$M_s = K_3 D + K_4$

$K_3 = 0.0172019699$

$K_4 = 6.2189875$ (M_s on Jan 1, 1972)

NOTE: K_4 is subject to update to current year. M_s is the orbital angle of the earth relative to the perihelion (point in earth's orbit at which the earth is closest to the sun).

$$S(1) = K_5 \sin L_s$$

$$K_5 = 0.39784368 \text{ ("tilt of sun's orbit")}$$

$$L = -2\pi E + K_6 \sin M_s - K_7 \sin (2L_s)$$

$$= \text{"Sun's apparent longitude"}$$

$$\left.\begin{aligned} K_6 &= 0.0334440 \\ K_7 &= 0.04127339 \end{aligned}\right\} \text{ elipticity corrections}$$

$$S(2) = \sqrt{1 - S(1)^2} \text{ Cos } L$$

$$S(3) = \sqrt{1 - S(1)^2} \text{ Sin } L$$

S(1), S(2), S(3) form a geocentric unit vector representing solar information required to compute the diurnal function; i.e., a unit vector originating at the earth's center, pointing at the sun.

The values accumulated to this point, for future use, are:

D = Number of days since Jan 0.0, 1968

IS = Seasonal index (an integer)

$$\left.\begin{aligned} S(1) \\ S(2) \\ S(3) \end{aligned}\right\} = \text{Geocentric unit vector pointing at the sun}$$

3.3.12.3.3 <u>Numerical Integration over the Transmission Path</u>: $\overrightarrow{STA}$ <u>is a</u> geocentric unit vector directed to the station under consideration; POSE is a geocentric unit vector directed to the estimated submarine position (i.e., R_1) as held by the OMEGA navigation processing routine.

Calculate: the cross-product,

$\overrightarrow{AX} = \overrightarrow{STA} \times \overrightarrow{POSE}$, to get a unit vector normal to the path of conduction from station to submarine receiver.

Calculate: θ_1, angle between $\overrightarrow{STA}$ & $\overrightarrow{POSE}$.

Note: For computing θ_2 and θ_3 it is sufficiently accurate to use the R_{ij} in the geodetic reference frame directly.

$$\Theta_1 = \text{Sin}^{-1}\left[\left|\overrightarrow{AX}\right|\right] \quad \text{where } \left|\overrightarrow{AX}\right| \text{ is } 0 < \Theta_1 < \pi$$

the absolute value of the vector $\overrightarrow{AX}$.

Calculate: $A_2 = -(\overrightarrow{AX} \cdot \overrightarrow{NP})$

A_2 is "The first magnetic parameter" and $\overrightarrow{NP}$ is a constant geocentric unit vector directed toward the magnetic north pole, and is given by:

$$\overrightarrow{NP} = (0.9664,\ 0.0044864,\ -0.25705)$$

Following the preceding calculations, we begin calculations to determine the diurnal effect for each frequency, along the path.

A numerical line integration is performed by summing effects at 0.01 radian (earth - central angle) intervals along the assumed conduction path. This is done by integrating inverse wavelength over the path. Initialize:

Θ_2	=	0	Spheroidal correction
Θ_3	=	0	Propagation correction
GG	=	0	Diurnal function average
M_1	=	0	Extraction matrix element for P1
M_2	=	0	Extraction matrix element for P2
M_3	=	0	Extraction matrix element for P3
C_{21}	=	1.0	Relative amount of higher modes
C_{11}	=	0	Relative amount of reconverted modes
$\overrightarrow{P}$	=	$\overrightarrow{STA}$	The first point of the integration is at the transmitter

P_1, P_2, P_3 are components of the integration position $\overrightarrow{P}$, oriented in the geocentric axis. This vector is initialized to the transmitter position coordinates, then moved along the propagation path in increments of $d\Theta$ radians as the integration progresses.

$d\Theta = 0.01$ radian

a) <u>Main Iteration Algorithm</u>

Calculate: $\text{Cos } X = \vec{P} \cdot \overrightarrow{STA}$

IF \ THEN	F (JF)	FM	FM_2	FM_3
Cos X < a	1	1	0	0
a ≤ Cos X ≤ b	$\dfrac{\text{Cos }(X-b) + K(JF,IS)(a-\text{Cos}X)}{a-b}$	$\dfrac{\text{Cos } X-b}{a-b}$	$\dfrac{a-\text{Cos } X}{a-b}$	0
b < Cos X	$\dfrac{K\ (JF \cdot IS)\ (1-\text{Cos } X)}{1-b}$	0	$\dfrac{1-\text{Cos } X}{1-b}$	$\dfrac{\text{Cos } X-b}{1-b}$

where a = -0.15

b = -0.04

k (JF, IS) from Table 3.3-5.

and JF is the frequency index, 1, 2, and 3, corresponding to 10.2, 13.6 and 11-1/3.

IS is the season index determined in Paragraph 3.3.12.3.1.

FM_1, FM_2, FM_3 are three "scatter diurnal" functions that apply to all three frequencies.

F (JF) is the diurnal function, and is calculated for each frequency.

On the first pass through the diurnal calculations (above) for a given station, a value $F(JF)_o$ is set equal to F(JF) for use in subsequent computations.

TABLE 3.3-5 DIURNAL CONSTANT (depends on frequency and season)

K (JF, IS)

JF = frequency index
IS = season index

IS \ JF	10.2	11.3	13.6
1	0.271	0.241	0.212
2	0.300	0.268	0.237
3 - 12	0.340	0.304	0.269
13 - 23	0.210	0.186	0.162
24	0.240	0.214	0.187

NOTE: For IS = 3, 12 and IS = 13, 23, K is at present constant. It is possible that this would not be so in a more sophisticated version.

$$A5 = \left| \vec{P} \cdot \vec{NP} \right| = \sin \phi$$

where $\vec{NP}$ is a constant vector to north mag pole

$$B1 = -A2/\sqrt{1 - (A5)^2} = \sin \theta$$

$$B2 = 1 - 2\,(B1)^2 = \cos 2\theta$$

$$AA_6 = \text{ABS}\left(\text{ATAN2}\left(\sqrt{1-(A5)^2},\ A5\right)\right) = |\phi|$$

= magnetic latitude

$$B4 = \frac{\pi}{2} - AA_6 = \frac{\pi}{2} - |\phi|$$

$$AA_5 = (B4)^3 = \left(\frac{\pi}{2} - |\phi|\right)^3$$

$$AA_2 = AA_5 * B_1 = \left(\frac{\pi}{2} - |\phi|\right)^3 \sin \theta$$

$$AA_3 = AA_5 * B_2 = \left(\frac{\pi}{2} - |\phi|\right)^3 \cos 2\theta$$

$$AA_4 = B4 * B2 = \left(\frac{\pi}{2} - |\phi|\right) \cos 2\theta$$

b) The following algorithm will provide compensation for auroral effects when integrating over a path vector near the pole. For values of constants refer to Table 3.3-6.

If	$AA_6 < AU(1)$	$I = 1$
	$AU(1) < AA_6 < AU(2)$	$I = 2$
	$AU(2) < AA_6 < AU(3)$	$I = 3$
	$AU(3) < AA_6 < AU(4)$	$I = 4$
	$AU(4) < AA_6$	$I = 1$

$$AAUR = a\ (I) * AA_6 * AA_6 + b\ (I) * AA_6 + c\ (I)$$

$$BAUR = Da\ (I) * AA_6 * AA_6 + Db\ (I) * AA_6 + Dc\ (I)$$

TABLE 3.3-6 AURORAL CONSTANTS

		1	2	3	4
	AU	1.02974	1.13446	1.16064	1.41371
All x 10^{-6}	a	0	310.04	- 1805.55	60.30
	b	0	- 641.39	+ 4179.73	-171.32
	c	0	+ 331.71	- 2414.90	+121.65
	Da	0	+ 930.13	- 5197.77	- 93.80
	Db	0	-1905.09	+11840.17	+206.28
	Dc	0	+ 975.47	- 6731.36	-104.13

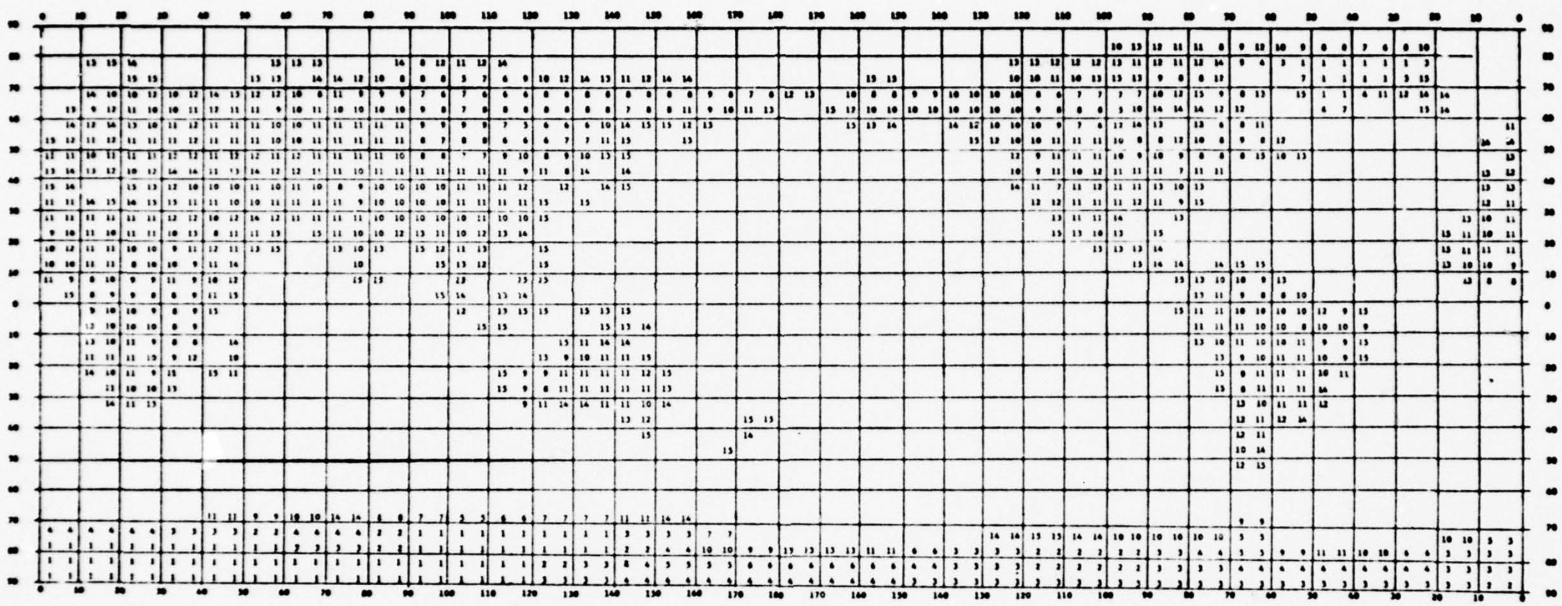
c) Determination of IC, the Conductivity Index

This algorithm takes the position vector $\vec{P}$ and searches the conductivity map to find the conductivity index IC of the region on the earth's surface corresponding to $\vec{P}$.

The conductivity map (Figure 3.3-8) has the following form:

For latitude north of 55°S, the earth is broken up into boxes each 5° by 5°.

For latitudes south of 55°S, the earth is broken up into boxes 5° in latitude and 10° in longitude.



BLANK => 14

10492

FIGURE 3.3-8 CONDUCTIVITY MAP

There are sixteen (16) conductivity levels ranging from 16 (sea water) to 1 (permafrost).

The conductivity of each box is the average conductivity of the earth's surface within the box, weighted according to the areas of each conductivity. The Westinghouse Conductivity Map was used.

d) Having determined the conductivity index, we continue the path integration:

$$A\ (JF) = \sum_{I=2}^{6} CAY\ (JF,\ I)\ AA_i + CAY1\ (JF,\ IC) + AAUR$$

$$B\ (JF) = \sum_{I=2}^{6} DCAY\ (JF,\ I)\ AA_i + DCAY1\ (JF,\ IC) + BAUR$$

$$\Delta\Theta_3(JF) = A\ (JF) + F\ (JF) * B\ (JF)$$

$$\Delta M_i(JF) = FM_i * B\ (JF)$$

The constants CAY, DCAY, CAY1, and DCAY1 are given in Tables 3.3-7 and 3.3-8.

TABLE 3.3-7 VALUES OF CAY AND DCAY

CAY (JF, I)

	10.2	11.3	13.6
1	323.0	291.0	242.0
2	Same	-0.4	Same
3	as	0.0	as
4	11.3	-0.65	11.3
5		0.0	
6		1.32	

DCAY (JF, I)

1	207.0	185.0	155.0
2	2.8	2.36	1.82
3	-1.5	-1.44	-1.43
4	0.65	0.65	0.65
5	4.70	4.22	3.38
6	-1.32	-1.32	-1.32

Multiply all by 10^{-6}

TABLE 3.3-8 VALUES OF CAY1 AND DCAY1

CAY1 (JF, IC)

IC \ JF	10.2	11.3	13.6
1	-27.0	-32.0	-40.0
2	-20.0	-27.0	-35.0
3	9.0	- 8.0	-23.0
4	33.0	36.3	27.5
5	24.6	32.7	44.0
6	16.3	25.3	38.5
7	7.9	19.1	33.2
8	3.2	14.8	30.0
9	- 0.2	12.0	27.6
10	- 3.0	9.2	25.6
11	- 5.1	7.5	23.8
12	- 6.4	6.2	22.9
13	- 7.2	5.2	22.2
14	- 8.0	4.5	21.5
15	- 8.8	3.8	21.0
16	- 9.0	3.9	20.8

Multiply all by 10^{-6}

DCAY1 (JF, IC)

IC \ JF	10.2	11.3	13.6
1	0.0	30.0	60.0
2	3.8	28.2	55.0
3	8.3	21.2	38.5
4	5.5	5.5	12.0
5	22.3	19.4	15.2
6	26.3	23.3	19.2
7	30.2	27.0	23.3

TABLE 3.3-8 (Continued)

IC \ JF	10.2	11.3	13.6
8	32.8	29.5	25.2
9	33.8	30.0	25.2
10	34.2	30.2	25.2
11	33.6	30.0	25.2
12	33.2	29.4	24.4
13	32.9	28.9	23.7
14	32.6	28.8	23.7
15	32.1	28.5	23.7
16	31.8	27.6	23.7

Multiply all by 10^{-6}

Compute: (for JF = 1, 2, 3)

$$\theta'_3(JF) = \theta_3\,(JF) + \Delta\theta_3\,(JF)$$

$$M'(I,JF) = M(I,JF) + \Delta M(I,JF) \qquad I = 1, 2, 3$$

$$GG'(JF) = GG\,(JF) + F\,(JF)$$

Set θ_3 (JF) = θ'_3 (JF), M (I,JF) = M' (I,JF), GG (JF) = GG' (JF)

$$C_{21}\,(JF) = C_{21}\,(JF) \cdot \alpha_o(JF) \cdot F(JF) + K_{21}\,(JF) \cdot \left[F(JF) - F(JF)_o\right]^2$$

$$C_{11}\,(JF) = C_{11}\,(JF) + K_{11}\,(JF) \cdot \left[F(JF) - F(JF)_o\right]^2$$

Set $F(JF)_o$ = F(JF)

where K_{21} and K_{11} are constants, defined for each frequency, and represent the excitation of 2nd mode and rexcitation of 1st mode; α_o is the relative nighttime attenuation of 2nd mode and is a function of frequency.

$\alpha_o(1) = 0.91$

$\alpha_o(2) = 0.925$

$\alpha_o(3) = 0.94$

$\theta'_2(JF) = \theta_2(JF) + C_1 \cdot P\ (1) \cdot P\ (1)$

$C_1 = -0.336 \times 10^{-4}$

e) Now test for end of the integration path

$\overrightarrow{TEST} = \vec{P} - \overrightarrow{POSE}$

If $\left|\overrightarrow{Test}\right| > (d\theta)^2$

then Increment $\vec{P}$

$\vec{P} = (\overrightarrow{AX} \times \vec{P}) \cdot \sin (d\theta) + \vec{P} \cdot \cos (d\theta)$

Return to Paragraph (a).

If $\left|\overrightarrow{Test}\right| \leq (d\theta)^2$

then correct for incremental integration

$\Delta\theta = n \cdot d\theta$

where n is number of increments

$$\theta_c = \frac{\theta_i}{\Delta\theta}$$

$\theta_2 = \theta_2\ \theta_c$

$\theta_3 = \theta_3\ \theta_c$

$M_1 = M_1\ \theta_c$

$M_2 = M_2\ \theta_c$

$M_3 = M_3\ \theta_c$

Add to θ_3 the excitation term based on the average F for the path (GG)

$$\theta_3 = \theta_3 + CAY(JF, 1) + \frac{d\theta * GG * DCAY(JF, 1)}{\theta_1}$$

where CAY(JF, 1), DCAY(JF, 1) are constants (Tables 3.3-7 and 3.3-8).

f) Combine the effects of second mode and reconverted first to compute an estimate of the variance on the predicted phase.

$\sigma^2_{ppi} = (C_{21} + C_{11} + .04)^2$ where i represents the station

Now convert the results for 11-1/3 and 13.6 kHz into wavelengths and also introduce the factor 0.9974 so that the results agree with conventional chart value.

C_4 is a constant, RAT(JF) is a constant 3-vector

$$\theta_1 = C_4 \, C_5 \, \theta_1 \, RAT(JF)$$

$$\theta_2 = C_4 \, C_5 \, \theta_2 \, RAT(JF)$$

$$\theta_3 = C_4 \, C_5 \, \theta_3 \, RAT(JF)$$

3.3.12.3.4 Glossary

θ_1	Central angle between STA and POSE
$\overrightarrow{NP}$	Constant vector to North Magnetic Pole
A_2	Magnetic parameter used in subroutine DELTH
θ_2	Spheroidal correction
θ_3	Propagation correction
GG	Diurnal function average
M_i, i = 1, 2, 3	Explanation matrix element for P_i, i = 1, 2, 3
C_{21}	Correction factor for higher propagation modes
C_{11}	Correction factor for reconverted first mode of propagation
DIURNAL	Subroutine, calculates diurnal function F

3.3.12.3.4 Glossary (continued)

DELTH	Subroutine, computes incremented change in θ_3, ($\Delta\theta_3$) and the M_i, (i.e., ΔM_i)
$\vec{P}$ P (I)	Station vector = $\overrightarrow{STA}$
C_1	Ellipsoidal correction constant
$d\theta$	Increment unit
C_4	Chart conversion factor
C_5	Nominal 10.2 wavelengths/radian
RAT(JF), JF = 1, 2, 3	Frequency conversion factor
CAY(i, 1) i = 1, 2, 3	Excitation constants in propagation prediction
DCAY (i, 1)	
K_i, i = 1, 2, 3, 4	Sun's position constants relating to L_S and M_S on 1 January 1968
K_5	Tilt of sun's orbit
K_6, K_7	Ellipticity corrections
K_8	Days in half month
K_9	Half months in year
α_o (i)	Night attenuation factor on each frequency
F_{OLD}	Previous value of F
$\overrightarrow{SUN}$	Sun vector described in earth frame
IS	Season Index used in propagation prediction
IC	Conductivity Index used in propagation prediction

3.3.12.3.5 Summary of Constants:

	Description		Value
NP (1), NP (2), NP (3)	Unit vector to north mag pole	3	0.9659, 0.004529, -0.2588
C_1	Ellipsoidal correction constant	1	-0.336×10^{-4}
$d\Theta$	Increment unit	1	0.01
CAY (1, 1)	Excitation constants	1	(see Table 3.3-6)
CAY (2, 1)		1	
CAY (3, 1)		1	
K_{11} (1)	Reconverted first mode excitation factor	1	6.7
K_{11} (2)		1	*
K_{11} (3)		1	*
K_{21} (1)	Second mode excitation factor	1	25.0
K_{21} (2)		1	*
K_{21} (3)		1	*
a	limits of cos X for	1	-0.15
b	transition region	1	-0.04
α_o (1)	Second mode relative	1	0.91
α_o (2)	Night	1	0.925
α_o (3)	Attentuation factor	1	0.94
RAT (1)	Frequency conversion factor	1	1.0
RAT (2)		1	10/9
RAT (3)		1	4/3
C_4	Chart conversion factor	1	0.9974
C_5	Nominal 10.2 wavelengths/radian	1	217.021
K (1, IS) K (2, IS) K (3, IS)	diurnal constant 72 IS = 1, 24		(see Table 3.3-8)
CAY (JF, I) DCAY (JF, I)	model constants 12 JF = 1,3 I = 2,5 12		(see Table 3.3-6)
CAY 1 (JF, IC) DCAY 1 (JF, IC)	conductivity 48 constants JF = 1,3 IC = 1, 16 48		(see Table 3.3-7)

3.3.12.3.5 Summary of Constants (continued)

	Description	Value
K_1		0.0172027914
K_2	L_S on 1/1/72	4.8632700
K_3		0.0172019699
K_4	M_S on 1/1/72	6.2189875
K_5	"tilt of sun's orbit"	0.39784368
K_6	ellipticity corrections	0.0334440
K_7	ellipticity corrections	0.04127339
K_8	days in a half month	15.2184
K_9	half months in a year	24.0

3.3.12.4 Outputs

Output	Units	Range	Resolution	Destination
θ_2	Cycles	0-±32	2^{-10}	Combinational Filter
θ_3	Cycles	0-±32	2^{-10}	Combinational Filter Control-Indicator-Panel
σ^2_{ppi}	$Cycles^2$	0-1	2^{-31}	Combinational Filter

3.3.13 Velocity and Heading Processing

3.3.13.1 Introduction

This algorithm processes the velocity and heading data which is input from either the E.M. Ship's Log (velocity) and the Mark 19 Repeater (heading), and/or the respective manual inputs from the Control-Indicator. If the data are from the external sources, the inputs will be smoothed before processing. This is not necessary for the manual inputs.

The submarine velocity input is resolved into the system axes (R_2 and R_3) and then corrected by velocity increments from the combinational filter.

3.3.13.2 Inputs

Velocity - From the E. M. Ship's Log synchro, or manually inserted from the Control-Indicator. Range: 0-35 knots

Heading - From Mark 19 Repeater synchro, or manually inserted from the Control-Indicator. Units in degrees

$\delta V_2, \delta V_3$ - Velocity corrections in knots to V_2 and V_3 from Combinational Filter

θ_p - System heading angle from Navigation Processing

$\left.\begin{array}{l}\text{MAN}\\\text{VEL}\\\text{LOG}\end{array}\right\}$ Velocity and Heading Mode markers via manual input from Control-Indicator

Input	Units	Range	Resolution	Origin
V_{TAS}	Knots	0 - 35	---	I/O
ψ_A	Rad.	0 - 2π	---	I/O
$\delta V_2, \delta V_3$	ft/sec	$\lvert V \rvert < 4096$	.125	Combinational Filter
θ_p		0 - 7π	$2^{-15}\pi$	Navigation

3.3.13.3 Processing

For the following, all inputs in degrees are converted to radians.

a) For velocity input from the Ship's Log: designate as V_{TAS}.
For heading input from Mark 19 Repeater, designate as ψ_A.
Smooth both by the routine following, and note that smoothing may be deemed unnecessary.

Set $\quad Z = (\psi_A - \psi_{Ao})$

Test $\quad |Z| > 4.4°\ ?$

Yes: $\psi_A = .02\ Z + \psi_{Ao}$

Continue

No: $\psi_{Ao} = \psi_A$

Set $Z = (V_{TAS} - V_{TASo})$

Test $|Z| > 12.2$ knots ?

Yes: $V_{TAS} = .02\ Z + V_{TASo}$

Continue

No: $V_{TASo} = V_{TAS}$

b) The program must check the velocity/heading mode set by the operator via the Control-Indicator: if MAN Marker true, use manual velocity heading inputs; if VEL Marker true, use manual velocity and smoothed heading; if LOG Marker true use both smoothed values above. Now let V_{AT} and ψ_A = velocity and heading input from either the output of the smoothing routine or the manual input (Control-Indicator). Resolve to system axes

$$V_2 = V_{AT} \text{ Sin } (\theta_p + \psi_A)$$

$$V_3 = V_{AT} \text{ Cos } (\theta_p + \psi_A)$$

c) Modify velocity by Combinational Filter corrections

$$V_{C2} = V_2 + \delta V_2$$

$$V_{C3} = V_3 + \delta V_3$$

3.3.13.4 Outputs

Outputs	Units	Range	Resolution	Destination
V_{C2}, V_{C3}	ft/sec	$\|X\| < 1024$	$1020/2^{15}$	Navigation Control-Indicator routines
V_{TAS}	ft/sec	$\|X\| < 1024$	$1020/2^{15}$	Control-Indicator
ψ_A	radians	$\|X\| < \pi$	$\pi/2^{15}$	Control-Indicator
V_2, V_3	ft/sec	$\|X\| < 1024$	$1020/2^{15}$	Tracking Filters

3.3.14 Navigation

3.3.14.1 Introduction

The iterative updating of the position matrix is performed by converting the velocity over the last iteration into the effective angular rotation about each of the system axes. These rotations are then used to generate the rotation update matrix. The update matrix is multiplied by the previous position matrix to yield the change of position, and this result is then added to the old position. Periodically the Kalman routine will be generating positional corrections. These will be added to and processed with the rotations generated from the velocity.

3.3.1.4.2 Inputs

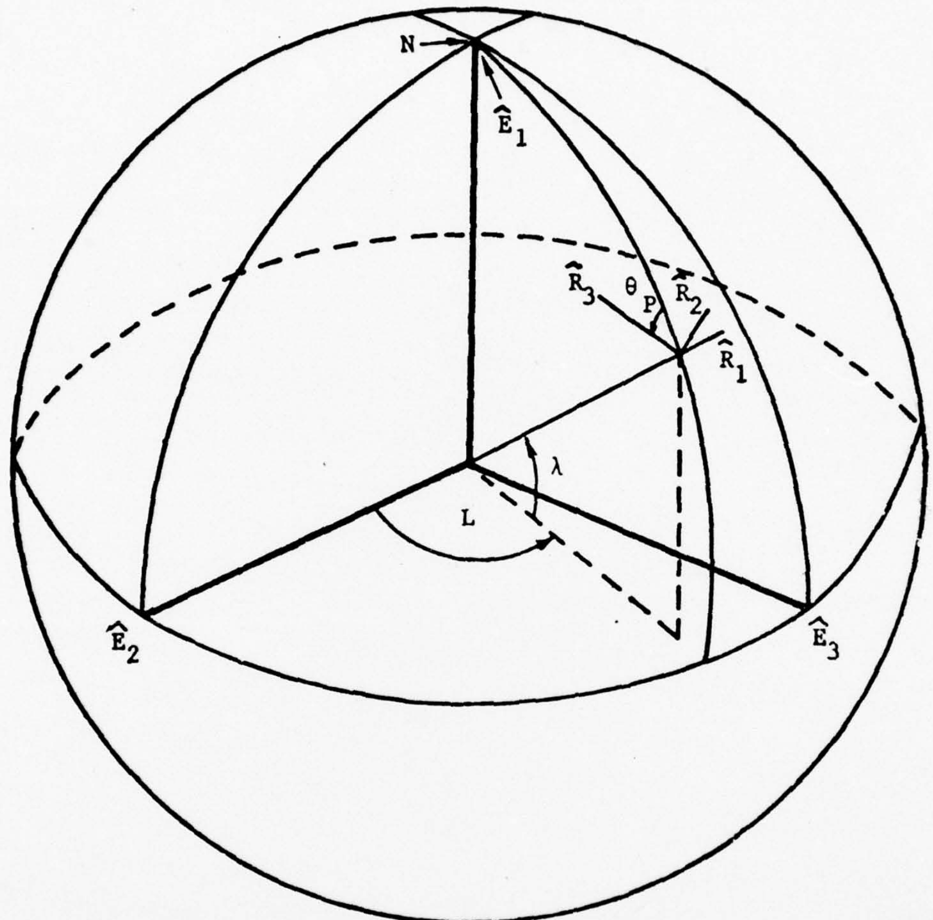
Inputs	Units	Range	Resolution	Origin
$\left[R_{ij}\right]_o$	None	$\lvert r_{ij}\rvert \leq 1$	2^{-31}	Control-Indicator routines
V_{C2}, V_{C3}	ft/sec	$\lvert X\rvert < 1020$	$1020/2^{15}$	Velocity Processing
$\delta\Theta_2, \delta\Theta_3$	rad	$\lvert X\rvert \leq \pi$	2^{-31}	Combinational Filter

3.3.14.3 Processing

a) Initialization

The following initialization routine will be used: 1) whenever the EP indicator is ON and latitude and longitude are input; or 2) whenever a fixed point is entered and the radial fix-point error is greater than 72 n mi.

Set $\Theta_p = 0$



λ, L are the latitude, longitude of the system

$\hat{R}_1$ is the local vertical

$\hat{R}_3$ is the system heading with θ_P as the angle CCW from north to $\hat{R}_3$

$\hat{R}_2$ is $\hat{R}_3 \times \hat{R}_1$

$\hat{E}_1$, $\hat{E}_2$ and $\hat{E}_3$ are the earth reference axes

FIGURE 3.3-9 OMEGA COORDINATE SYSTEM

r_{11} = Sin λ

r_{12} = Cos λ Cos L

r_{13} = Cos λ Sin L

r_{21} = Cos λ Sin Θp

r_{22} = -Sin L Cos Θp -Sin λ Cos L Sin Θp

r_{23} = Cos L Cos Θp -Sin λ Sin L Sin Θp

r_{31} = Cos λ Cos Θp

r_{32} = Sin L Sin Θp -Sin λ Cos L Cos Θp

r_{33} = -Cos L Sin Θp -Sin λ Sin L Cos Θp

b) R_{ij} Update

$$\Delta\Theta_2 = -\left[1 + e\,(1-2\,r_{11}^{\,2} + r_{31}^{\,2} - r_{21}^{\,2})\right] \frac{V_{C3}\,\Delta t_{NAV}}{R_o}$$

$$-2e\, r_{21}\, r_{31} \frac{V_{C2}\,\Delta t_{NAV}}{R_o} + \delta\Theta_2$$

$$\Delta\Theta_3 = \left[1 + e\,(1-2\,r_{11}^{\,2} - r_{31}^{\,2} + r_{21}^{\,2})\right] \frac{V_{C2}\,\Delta t_{NAV}}{R_o}$$

$$+2e\, r_{21}\, r_{31} \frac{V_{C3}\,\Delta t_{NAV}}{R_o} + \delta\Theta_3$$

where R_o = Mean equatorial radius of earth

e = Earth's ellipticity constant

Δt_{NAV} = Time intervals between updates of navigation equations

$\delta\Theta_2$ and $\delta\Theta_3$ will remain zero until updated by combinational filter.

$$[\Theta] = \begin{bmatrix} -\frac{(\Delta\theta_2^{\,2} + \Delta\theta_3^{\,2})}{2} & \Delta\theta_3 & -\Delta\theta_2 \\ -\Delta\theta_3 & -\frac{\Delta\theta_3^{\,2}}{2} & \frac{\Delta\theta_2\Delta\theta_3}{2} \\ \Delta\theta_2 & \frac{\Delta\theta_2\Delta\theta_3}{2} & -\frac{\Delta\theta_2^{\,2}}{2} \end{bmatrix}$$

$$R_{ij_{new}} = R_{ij_{old}} + [\Theta]_{3x3}\ R_{ij_{old}}$$

$$\Theta p = \mathrm{TAN}^{-1}\left[\frac{r_{21}}{r_{31}}\right]$$

Exit

c) The following internal parameters are used for the above:

Internal Parameter	Units	Range	Resolution
$\Delta t_{NAV}/R_o$	Sec/Ft	$1/2.0926 \times 10^8$	10^{-8}
e	---	1/297	10^{-5}

3.3.14.4 Outputs

Output	Units	Range	Resolution	Destination
Θp	rad	$0\text{-}2\pi$	$2^{-15}\pi$	Velocity Processing
$[R_{ij}]$	None	$\lvert r_{ij}\rvert \leq 1$	2^{-31}	Combinational Filter, Antenna Switching Matrix, Control-Indicator

3.3.15 Control-Indicator Panel Requirements

3.3.15.1 Introduction

The Control-Indicator Panel is the interface between the operator and the OMEGA system. Associated with the panel are computer routines, some of which are used for initialization while others are iterated or used on demand. These routines are explained and defined in the following paragraphs. Both Insertion and Display routines are presented.

INSERT:
- Submarine present position
- Date and time
- Data for fixed destination
- Data for Point of Intercept (rendezvous)
- Velocity and Heading source selection

DISPLAY:
- Submarine present position
- Positional variance estimate
- Date and time
- Submarine velocity and heading
- Submarine corrected velocity and track angle
- Range and bearing to fixed destinations
- Time enroute and course to fixed destinations
- Heading and velocity of moving destination
- Time enroute and course to moving destination
- Position of point of intercept (rendezvous)
- Station-to-station LOP
- Relative OMEGA signal coherency
- Relative OMEGA signal strengths
- Bite Failure Status

3.3.15.2 Inputs

Input	Units	Range	Resolution	From
FLOAT	Marker	---	---	Toggle Switch
POS UNC	"	---	---	Combinational Filter
AMB	"	---	---	Combinational Filter
BIT	"	---	---	Built-in-test
SYSTEM FAIL	"	---	---	Bias, Scale Factor (3.3.4), Built-in Test (3.3.16), BIT Equipment (3.3.17)
SYNC	"	---	---	Synchronization
SIGLOSS	"	---	---	Base Station Selection
STAT MRH_i $i=A,\cdots,H$	"	---	---	C-I Input
POS CLASS (A,B or C)	"	---	---	C-I Input
V_{ci} $i=2,3$	ft/sec	$\lvert X \rvert < 1020$	$1020/2^{15}$	Velocity Processing
V_{TAS}	"	"	"	Ships E.M. Log via Velocity Processing
V_D	"	"	"	C-I Input
ψ_A	Radians	$\lvert X \rvert < 2\pi$	$/2^{15}$	Velocity Processing or MK19 Repeater
α_D	"	"	"	C-I Input
λ_D, λ_{Di} $i=0,1,...,9$, PI	Degrees & Minutes N or S	$\lvert X \rvert < 180^o$	0.1 min	C-I Input
L_o, L_{Di} $i=0,1,...,9$,PI	Deg. + Min E or W	"	"	C-I Input

3.3.15.2 Inputs (continued)

Input	Units	Range	Resolution	From
DATE	Yr/mo./day	$\|X\| \leq 73/12/31$	---	C-I Input
GMTo	hrs/min/sec	$\|X\| \leq 24/60$	1/0.1	C-I Input
r_{ij}	--	$\|X_{ij}\| < 1$	2^{-31}	Navigation
TIME	sec	$2^{-31}(0.005)$	0.005 Sec	Executive
θp	Radians	$\|X\| \leq \pi$	2^{-15}	Navigation
$\theta_{3_{ikj}}$	"	$\|X\| \leq 2\pi$	2^{-15}	Propagation Prediction
$\hat{\phi}_{ikj}$	Cycles	$\|X\| < \pi$	"	Tracking Filter
P_{ii} i=1,2	$(\text{Cycles})^2$	$\|X\| < 0.0418^2$	0.0418^2 $\times 10^{-6}$	Comb. Filter
$\sigma^2_{\phi\phi_{ikj}}$	$(\text{Cycles})^2$	"	"	Tracking Filter
$NCTR_{ikj}$	Counts	$X \leq 99$	1	Comb. Filter
ND_{ikj}	Counts	$X \leq 9$	1	Tracking Filter
C_D	$\text{cnts}^2/.1$ sec	$0\text{-}10^4$	----	Synchronization
ΔC	"	"	----	"

3.3.15.3 Processing

3.3.15.3.1 Status and Malfunction Indicators:

a) FLOAT and LOOP indicators

The manually operated toggle switch is either in the FLOAT or LOOP position. The toggle position controls a discrete computer input which in turn actuates either the FLOAT or LOOP indicators.

b) POS UNC

Actuated by POS-UNC marker from the combinational filter. Indicates both an uncertainty in system position (>4 n miles) and that the combinational filter has entered the difference-frequency mode.

c) AMB

Actuated by a marker from the combinational filter. Indicates that more than one state vector has been computed and that an ambiguity in system position exists.

d) SYSTEM MALF

Actuated by BIT marker from self-test routines. Indicates an out-of-tolerance condition somewhere in the system,

e) SYNC

Actuated by the SYNC marker from synchronization routine. SYNC light is on during synchronization process.

f) SIG LOSS

Actuated by the SIG LOSS marker from the Base-Station Selection procedures. Indicates signal volume input to receiver is less than tolerable.

g) PANEL TEST

Described in TEST procedures, paragraph 3.3.16.

3.3.15.3.2 Control Switches:

a) DIM

This designates a potentiometer on the console which varies the intensity of the front panel indicators.

b) PANEL HOLD

At the time PANEL HOLD is depressed the HOLD MRK is set true and the data indicated below is transferred, as is, to special registers whence they may be displayed as desired. The star on the variables represents data in the HOLD mode. If PANEL HOLD is not depressed and any of the below data is displayed, that data will change on the display reflecting normal updating. At the time PANEL HOLD is again depressed the HOLD MRK is set false.

R^*_{ij}	Current submarine position
V^*_{ci}, ψ^*_A	Calculated velocity and track angle
V^*_{TAS}, ψ^*_A	Ship's E.M. log and MK 19 heading
R^*_{Di}, ψ^*_{Di}	Range and bearing to selected destination i.
ETE^*_i	Estimated time to selected destination i.
$DATE^*$, GMT^*	Date - Greenwich Mean Time.

c) POWER

This switch turns power on and off. In the off position all system power is turned off. In the on position the computer power supply is activated and power applied to the whole system. The computer then goes through an automatic turn-on sequence and into a computational mode selected by the panel

d) DISPLAY

The illuminated DISPLAY enables the operator to initiate a data display routine.

e) CLEAR

The illuminated CLEAR enables the operator to initiate the panel quiescent state so that a new Control panel "Display" or "Insert" sequence can be started.

3.3.15.3.3 INSERT Routines:

a) Insert Submarine Present Position:

The inserted position of the submarine is treated in two different ways as a function of whether it is a Present Position insertion used to initialize the system or whether it is a Position Fix used to update the system.

The first position insert is treated as a Present Position. The R_{ij} matrix is initialized, using the inserted latitude and longitude, and the appropriate class of fix marker is set for the Kalman Routine, provided the existing Present Position is not accepted without change. Subsequent position inserts before sync is obtained are treated as a first insert. The EP lamp is turned off. All other position

inserts are treated as Position Fixes. These are utilized as a Kalman measurement input and are incorporated into the system via Kalman Processing. The Kalman inputs are computed. These include the position differences between the system and the inserted values in the North and East directions, the extraction matrix elements for each of these measurements and the noise scaler. Also a marker is set to inform the Kalman routine that a position measurement has been made.

1) Test First Insert = true? (i.e., are ET, EP or SYNC indicators illuminated?) yes, go to 2
no , go to 5

2) $r_{11} = \sin \lambda_o$

$r_{12} = \cos \lambda_o \cos L_o$

$r_{13} = \cos \lambda_o \sin L_o$

$r_{21} = 0$

$r_{22} = -\sin L_o$

$r_{23} = \cos L_o$

$r_{31} = \cos \lambda_o$

$r_{32} = -\sin \lambda_o \cos L_o$

$r_{33} = -\sin \lambda_o \sin L_o$

were $N = > \lambda_o$ positive $S = > \lambda_o$ negative

$E => L_o$; $W => 360^o - L_o$

3) POS CLASS = i i = A, B, C

4) Initial: Reset TF MKR = true
Cold Start MKR = true; exit

5) $\theta_p = \tan^{-1} \left(\frac{r_{21}}{r_{31}}\right)$

6) $\delta P_N = \left[\tan^{-1}\left(\frac{r_{11} \cos \theta_p}{r_{31}}\right) - \lambda_o\right] K_{RD}$

7) $L_{A/C} = \tan^{-1} \left(\frac{r_{13}}{r_{12}}\right)$

8) $\delta P_E = (L_{A/C} - L_o) \cos \lambda_{A/C} K_{RD}$

9) **Test:** Is $\sqrt{\delta P_N^2 + \delta P_E^2} > 72$ n miles?

Yes: Go to 2

No: Continue

10) $C_{POS} = \sigma^2 (\delta \text{ POS INSERT})_i$; where

$i = A, B, C$

i	δ Pos Insert
A	0.5 n miles
B	5.0 n miles
C	20.0 n miles

11) Set POS MRK = true

exit

b) Insert Date and Time

Whenever the operator inserts a new Date and Time the Kalman routine must be informed via a marker bit so that it can appropriately reinitialize its parameters. If the time is inserted in response to the illuminated ET indicator, indicating a system restart, then set:

COLD START MKR = True

The inserted Month and Day are saved for the Propagation Prediction season index determination. Then the inserted DATE and TIME is converted to a single number representing the current time. This conversion must account for the number of days in a month and leap years.

The present value of the TIME register is subtracted from the inserted current time to give the time GMT(o) at turn-on.

c) Insert Data for Fixed Destinations

The operator may insert up to ten fixed locations for which a great circle course may be desired, based upon the position of the submarine at the time the data is desired. To do this the latitude (λ) and longitude (L) and the reference number (i; 0-9) are stored in the table of destination points. Thus, where λ_D, L_D represent the position of a destination:

$$\left.\begin{array}{l} \lambda_{Di} = \lambda \\ L_{Di} = L \end{array}\right\} \quad 0 \leq i \leq 9.$$

AD-A047 906 NORTHROP CORP HAWTHORNE CALIF ELECTRONICS DIV F/G 17/7
COMPUTER PROGRAM PERFORMANCE SPECIFICATION. VOLUME I. RADIO NAV--ETC(U)
JUL 73 N00039-73-C-0209

UNCLASSIFIED NORT-73-48-VOL-1 NL

3 OF 3
AD
A047906

END
DATE
FILMED
1-78
DDC

d) <u>Insert Data for Point of Intercept (Rendezvous)</u>

This routine is a composite of two INSERT operations:

- INSERT MOVING DESTINATION, and
- INSERT MOVING DESTINATION VELOCITY, V_D, AND HEADING, α_D

Both must be inserted for proper operation. However, a zero moving-destination velocity may be entered if the routine is to be used as a fixed destination. The computer program will then calculate the following which may be displayed:

- Submarine range and bearing to destination (point of intercept)
- Present position of moving destination
- Estimated time enroute and course
- Present position of point of intercept (lat. long.)

The moving destination is, presumably, a second vehicle which will also arrive at the rendezvous point at the same time. In this sense the rendezvous point is the fixed destination while the moving second vehicle is the moving destination.

The following routines take place upon insert of position, velocity and heading of the moving destination. Define the following:

λ_D, L_D = latitude, longitude of moving destination

V_D, α_D = velocity, heading of moving destination

D = position representation of moving destination

R = position representation of submarine

E subscript representation in earth-fixed coordinates

The following steps 1 through 5 will be done initially and at any time a new position, velocity or heading fix is inserted. Step 6 will be iterated once per second.

1) Convert λ_D, L_D to position $\bar{D}_E$

$$\vec{D}_E = (D_{E1}, D_{E2}, D_{E3}) \text{ where } D_{E1} = \sin \lambda_D$$

$$D_{E2} = \cos \lambda_D \cos L_D$$

$$D_{E3} = \cos \lambda_D \sin L_D$$

2) Obtain earth radius ρ_D of moving destination at current position.

$$\rho_D = \rho_o(1 - K \cdot D_{E1}^2); \quad \rho_o \text{ is equatorial radius of earth}$$

K is a constant

3) Obtain unit velocity in earth-fixed coordinates

$$\hat{V}_E = (V_{E1}, V_{E2}, V_{E3}) \text{ where } D_{RAD} = (D_{E2}^2 + D_{E3}^2)^{\frac{1}{2}}$$

$$V_{E1} = D_{RAD} \cos \alpha_D$$

$$V_{E2} = -\frac{D_{E1} D_{E2}}{D_{RAD}} \cos \alpha_D - D_{E1} \sin \alpha_D$$

$$V_{E3} = -\frac{D_{E1}\ D_{E3}}{D_{RAD}} \cos \alpha_D + \frac{D_{E2}}{D_{RAD}} \sin \alpha_D$$

4) Obtain great circle route β with unit velocity of moving destination

$$\vec{\beta}_E = \vec{D}_E \times \hat{V}_E$$

$$= (\beta_{E1}, \beta_{E2}, \beta_{E3})$$

5) Obtain angular velocity, V_β of moving destination in radians/sec. (This is referred to as R2 update and is done once per second.)

$$V_\beta = \frac{V_D}{\rho_D}$$

6) Position update of moving destination.

$$\vec{D}_E = \vec{D}_E + V_\beta \Delta t(\vec{\beta}_E \times \vec{D}_E)$$

and $\Delta t = 1$

For data display routines, see Display of Moving Destination routines.

3.3.15.3.4 Display Routines:

a) Display Submarine Present Position

The current submarine position as defined by latitude and longitude will be extracted from the R_{ij}'s If the HOLD button has been depressed the R_{ij}'s will be those stored upon its depression. The following calculations must be made.

1) Test HOLD Marker

If true use r_{ij}^* in following equations

If false use r_{ij} in following equations

2) $\lambda_{pp} = \tan^{-1}\left(\frac{r_{11}}{(r_{12}^2 + r_{13}^2)^{1/2}}\right)$

If $\lambda_{pp} \geq 0$ then left projection = N

$\lambda_{pp} < 0$ then left projection = S

3) $L_{pp} = \tan^{-1}\left(\frac{r_{13}}{r_{12}}\right)$

If $0 \leq L_{pp} < 180^\circ$ then right projection = E

$180^\circ \leq L_{pp} < 360^\circ$ then $L_{pp} = 360^\circ - L_{pp}$

and right projection = W

b) Display Position Variation (VAR)

Upon depression of the illuminated VAR button the current estimate of positional variance from the combinational filter will be displayed.

This is obtained from the covariance matrix.

$$PV = \sqrt{(P_{11} + P_{22})} \left[\frac{1}{\sqrt{2}} \right]$$

Convert PV to n miles.

c) Display Date and Time

The present value of the TIME register is added to GMT(o) to obtain the current real time in GMT. This number is then converted to YEAR, MONTH, DAY, HOURS, MINUTES and SECONDS for display.

d) Display Submarine Velocity and Heading (AUTO H/S)

The current submarine velocity is V_{TAS} and is obtained from Velocity and Heading Processing (Paragraph 3.3.13). It is a smoothed value of the E.M. Ship's Log input and is displayed on the left numeric readout to tenths of knots.

The current submarine heading is designated ψ_A and is either the manual input or the smoothed value of the Mark 19 Repeater input, depending upon the velocity and heading mode in use. It is converted from radians to degrees and displayed on the right numeric readout.

e) Display CAL H/S

The OMEGA velocity is computed by taking the square root of the sum of the squares of the two craft velocity components.

The Track Angle is computed by finding the heading of the velocity vector relative to system axis and then using this in conjunction with system heading to yield the heading with respect to North.

If PANEL HOLD has been depressed, then the information used in this computation is that which was stored on its depression.

1) Test HOLD MRK True $\Rightarrow$ use r_{ij}^*, V_{ci}^*

False $\Rightarrow$ use r_{ij}, V_{ci}

2) $V_c = (V_{c2}^2 + V_{c3}^2)^{\frac{1}{2}}$

3) $\psi_V = \tan^{-1}\left(\frac{V_{c2}}{V_{c3}}\right) - \theta_p$ and covert to degrees

where

$$\theta_p = \tan^{-1}\left(\frac{r_{21}}{r_{31}}\right)$$

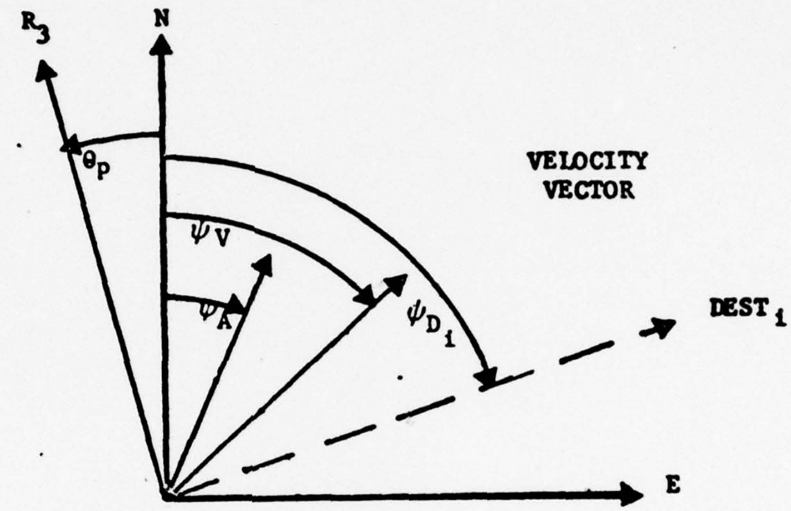
f) Display Range and Bearing

The angular distance between the submarine and the destination point is computed by taking the "dot" product of the two vectors. The distance is then achieved by multiplication by the earth radius.

The angle between the R_3 vector and the destination vector D_1 is computed by taking appropriate "dot" products with the R_2 and R_3 axex to generate the sin and cos of this angle. The actual bearing angle is computed from this angle with respect to the R_3 axis and θ_P. Figures 3.3-10 and 3.3-11 depict some of this information.

If PANEL HOLD has been depressed, then the information used in this computation is that which was stored in its depression.

The bearing to destination will be displayed to a tenth of a degree in the left numeric readout. The range to destination will be displayed in nautical miles on the right.



10759

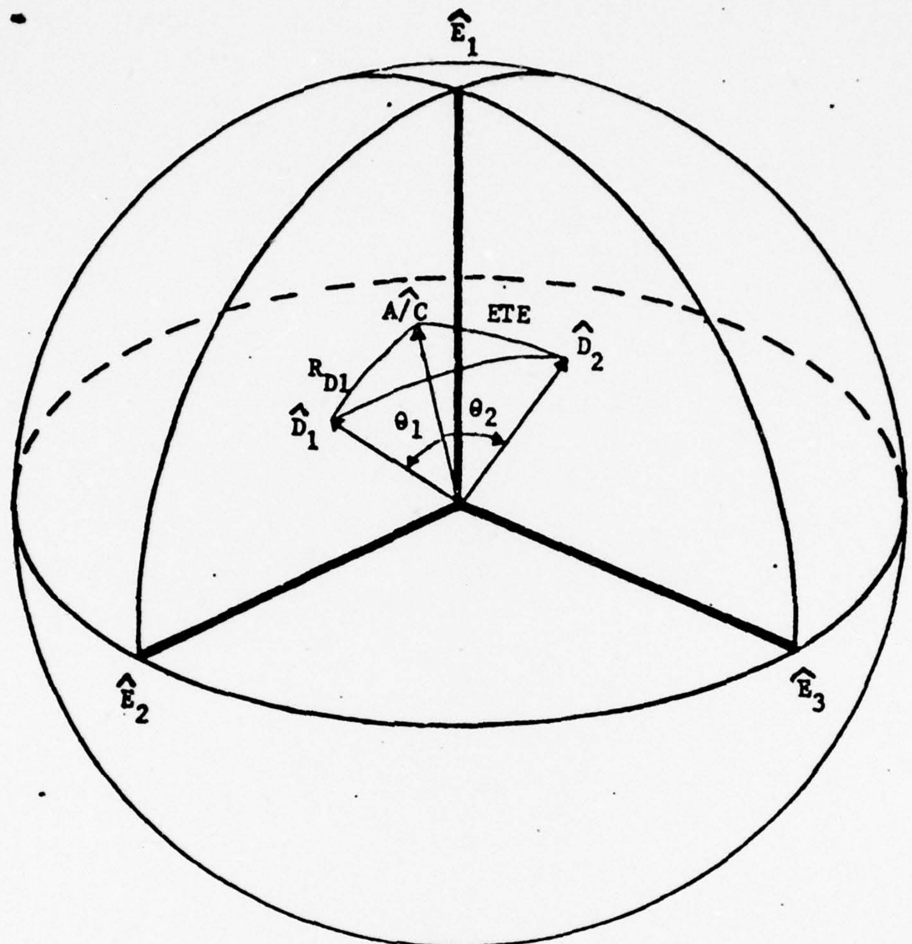
ψ_A = Ship Heading HDG

ψ_V = Ship Velocity Track - TK

ψ_D = Course to Selected Destination

θ_P = System Heading N to R_3 CCW

FIGURE 3.3-10 SYSTEM AZIMUTHAL RELATIONSHIPS



$\hat{E}_i$ = Earth Reference Axes

$\widehat{A/C}$ = Ship Position Vector

$\hat{D}_i$ = Destination i Position Vector

θ_i = Central Angle Between A/C and D_i

R_{Di} = Range Between A/C and D_i

= $R_o \theta_i$ where R_o is earth radius

ETE_i = Estimated Time Enroute Between A/C and D_i

= $\frac{R_{Di}}{V_c}$ where V_c is craft velocity

FIGURE 3.3-11 SYSTEM VECTOR RELATIONSHIPS

1) Test HOLD MRK true $\Rightarrow$ use r_{ij}^*

false $\Rightarrow$ use r_{ij}

2) $\hat{D}_i = \sin \lambda_{Di} \hat{E}_1 + \cos \lambda_{Di} \cos L_{Di} \hat{E}_2 + \cos \lambda_{Di} \sin L_{Di} \hat{E}_3$

3) $\psi_{Di} = -\theta_p - \tan^{-1}\left(\frac{-\hat{D}_i \cdot \hat{R}_2}{\hat{D}_i \cdot \hat{R}_3}\right)$; $\theta_p = \tan^{-1} \frac{r_{21}}{r_{31}}$

4) $R_{Di} = R_o \tan^{-1}\left(\frac{|\hat{D}_i \times \hat{R}_i|}{\hat{D}_i \cdot \hat{R}_i}\right)$

g) <u>Display Estimated Time Enroute and Course (CSE/ETE) to Fixed Destination</u>

The course is defined exactly the same as Bearings, and therefore the computation is the same (Refer to Display Range and Bearing, paragraph f, above).

The Estimated Time Enroute is computed by computing the range and dividing it by the component of craft velocity in that direction.

If PANEL HOLD has been depressed then the information used in this computation is that which was stored on its depression.

1) Test HOLD MRK True, then use r_{ij}^*, V_{ci}^*

False, then use r_{ij}, V_{ci}

2) ψ_{Di} From Range and Bearing Display routine

3) $ETE_i = R_{Di} \Big/ \left[V_{c3}^2 + V_{c2}^2\right]^{\frac{1}{2}}$

h) <u>Display Heading and Velocity of Moving Destination</u>

This routine is associated with the time update equation in paragraph d, insert for Point of Intercept, which should be referenced by the reader for derivations.

Let $\vec{\beta}_E$ = great circle route of moving destination defined in earth-fixed coordinates

$\vec{D}_E$ = present time-updated position of moving destination

α_D = heading of moving destination.

Then

$$\alpha_D = \mathrm{Tan}^{-1}\left(\frac{\beta_{E1}}{(\beta_{E2}D_{E3} - \beta_{E3}D_{E2})}\right) \text{ , convert to degrees}$$

The velocity display will be that which was last inserted by the operator for the moving destination.

i) Display Present Position of Moving Destination

The position, course and speed of the moving destination were previously initialized, then tracked with time updates every second. The position updating process for position is described in paragraph d, Insert for Point of Intercept, and is indicated as:

$$\vec{D}_E = (D_{E1}, D_{E2}, D_{E3})$$

To convert to latitude and longitude:

$$\lambda_D = \mathrm{Tan}^{-1} \frac{D_{E1}}{\left[D_{E2}^{\ 2} + D_{E3}^{\ 2}\right]^{\frac{1}{2}}}$$

$$L_D = \mathrm{Tan}^{-1} \frac{D_{E3}}{D_{E2}}$$

j) Display Position of Point of Intercept (referred to as RZ time update)

Upon insertion of the heading, speed and position of the second vehicle with which a rendezvous will be made the computer program will maintain an updated position (see d, Insert for Moving Destination). To display the point of intercept the following routine will use the time update equation for point of departure, which is:

1) $\vec{D}_E = \vec{D}_E + V_\beta \ \Delta t(\vec{\beta}_E \times \vec{D}_E)$

where V_β = angular velocity of moving destination along great circle course in radians/sec.

Δt - update rate of once per second

$\vec{\beta}_E$ = moving destination route with unit velocity

$\vec{D}_E$ = position of moving destination

and subscript E represents the earth-fixed reference frame

Let $\vec{C}_E = \vec{\beta}_E \times \vec{D}_E$

$= (C_{E1}, C_{E2}, C_{E3})$

$\vec{R}_1$ local vertical vector of OMEGA submarine

$= (R_{11}, R_{12}, R_{13})$ from R_{ij} matrix.

Now convert D and C to local geodetic vertical coordinates:

$D_{L1} = \vec{D}_E \cdot \vec{R}_1$

$C_{L1} = \vec{C}_E \cdot \vec{R}_1$

$\gamma = \mathrm{Tan}^{-1} (C_{L1}/D_{L1})$

The next equation must be solved for t by the iteration procedure following.

$$f(t) = (D_{L1}^2 + C_{L1}^2)^{\frac{1}{2}} \mathrm{Cos}(V_\beta t - \gamma) - \mathrm{Cos}(V_s t) = 0$$

where V_S = OMEGA submarine velocity along track.

$= (V_{C1}^2 + V_{C2}^2)^{\frac{1}{2}} / \rho_p$

$\rho_p = \rho_o(1 - K \sin^2 \lambda_p)$

λ_p = latitude present position (OMEGA)

ρ_o = earth radius

2) Iteration initialization

If $\gamma > 0$ and $\frac{\gamma}{V_\beta} < 5$ hrs.

Set $t = \frac{\gamma}{V_\beta}$, $\Delta t = 10 - \frac{\gamma}{V_\beta}$, and Marker A true

Otherwise set t = 5 hrs, Δt = 5 hrs.

3) Set $\Delta t = \Delta t/2$ and compute f(t) above

If $f(t) < 0$,

Set $t = t_{OLD} + \Delta t$

Go to 4)

If $f(t) > 0$

and if marker A is false

then $t = t_{OLD} - \Delta t$

Or if marker A is true

then $\Delta t = \frac{t_{old}}{2}$

$t = t_{OLD} - \Delta t$

4) Reset Marker A to False and test Δt

$\Delta t = \Delta t/2$

If $\Delta t > 1$ second go to (3) and continue

If $\Delta t < 1$ second, save t and continue

$t_{ETE} = t$

5) Compute Intercept Position $\vec{P}_{IE}$

$$\vec{P}_{IE} = \vec{D}_E \mathrm{Cos}(t_{ETE} V \beta) + (\vec{\beta}_E \times \vec{D}_E) \mathrm{Sin}(t_{ETE} V \beta)$$

$$= P_{IE1}, P_{IE2}, P_{IE3}$$

6) Compute latitude and longitude of point of intercept

$$\lambda_{PI} = \mathrm{Tan}^{-1} \frac{P_{IE1}}{\left(P_{IE2}^2 + P_{IE3}^2\right)^{1/2}}$$

$$L_{PI} \quad \mathrm{Tan}^{-1} \frac{P_{IE3}}{P_{IE2}}$$

k) <u>Display Estimated Time Enroute and Course (CSE/ETE) to Moving Destination</u>

This display uses the same information as in j) Display Position of Point of Intercept. Consequently the same routine is used and t_{ETE} (in seconds) is converted to hours and displayed.

Let T_{P1} = time in hours to moving destination.

$$T_{P1} = \frac{t_{ETE}}{3600}$$

To obtain the course to point of intercept it is necessary to obtain the latitude and longitude by the procedure described in paragraph k, Display Position of Point of Intercept, and then apply the "Bearing" routines from g, Display Range and Bearing.

l) <u>Display LOP</u>

This procedure will be iterated twice for each of the station-difference pairs selected by the operator.

1) The station difference pair desired by the operator will be presented in the normal chart order. Let (m-n) represent the LOP difference desired. Let j represent the frequency selected by the operator. LOP's using the base station are corrected for the base station to non-base station time delay contained in the tracking filters.

Test: Does base-station = n?

Yes: Then set $LOP_{mnj} = \hat{\phi}_{mnj} - (t_m - t_n)\frac{\hat{\phi}_n}{10} + 900$

No: Continue

2) Test: Does base-station = m?

Yes: Then set $LOP_{mnj} = -\left[\hat{\phi}_{nmj} - (t_n - t_m)\frac{\hat{\phi}_m}{10} + 900\right]$

No: Continue

3) Set $LOP_{mnj} = \hat{\phi}_{mbj} - (t_m - t_b)\frac{\hat{\phi}_b}{10} - \left[\hat{\phi}_{nbj} - (t_n - t_b)\frac{\hat{\phi}_b}{10}\right] + 900$

EXIT: Display LOP_{mnj}

m) <u>Display COH</u>

Upon depression of the illuminated COH button either six two-digit coherency values will be displayed in the registers or three four-digit numbers. These values are derived from either a station-base, or base-base pair respectively and all three frequencies (the particular station has been preselected).

1) <u>TEST</u>. Is station selected the base station (i.e., $i = k$)?

No: In the following subscript i represents the station selected, k represents the base selected and j represents the frequency (j=1, 2 or 3).

Let ϕ_{ikj} represent the phase difference value in the tracking filter for i and k on j, less the integer lane count.

COH_{ikj} represent the coherency value for same,

θ_{3ikj} represent the propagation corrections for same.

Then $COH_{ikj} = \phi_{ikj} - \theta_{3ikj} - (t_i - t_k)\,\hat{\phi}_{ki}/10 \quad j = 1,2,3$

$j = 1 = 10.2$ kHz $\quad j = 2 = 13.6$ kHz $\quad j = 3 = 11\ 1/3$ kHz

2) Display in the first pair of digits of left indicator:

$COH(11.3-10.2) = COH_{ik3} - COH_{ik1}$

Display in the second pair of digits of left indicator:

$COH(13.6-11.3) = COH_{ik2} - COH_{ik3}$

Display in the third pair of digits of left indicator:

$COH(13.6-10.2) = COH_{ik2} - COH_{ik1}$

Display in the first pair of digits of right indicator: COH_{ik1}

Display in the second pair of digits of right indicator: COH_{ik3}

Display in the third pair of digits of right indicator: COH_{ik2}

3) If yes - Display in first four digits of left indicator: ϕ_{kk1}

Display in last pair of left and first pair of right: ϕ_{kk2}

Display in last four digits of right indicator: ϕ_{kk3}

NOTE: The base tracking filter contains the phase difference between successive 10-second measurements.

n) Display CCOH

The right-hand display is identical to the values displayed when COH is displayed. The three pairs on the left display are the fractional part of the chart value, where the chart values are computed based on the present position contained in the RIJ matrix.

o) Display NCTR

The illuminated NCTR enables the operator to display the number of tracking filter dumps to the combinational filter for each station and verifies that this data is displayed. The 12 digits of the display are partitioned in units of four digits: four for the station-base or base-base pair selected on each frequency. On each frequency the first two digits will represent the total number of times that the data from the tracking filter selected has been used by the combinational filter to update position. The third digit is N_{Dj}, the N counter from that tracking filter, and the fourth digit is σ^2_{Dj}, the phase variance of the data in the tracking filter.

1) $NCTR_{Dj} = NCTR_{ikj}$ from the combinational filter

2) $N_{Dj} = N_{Dikj}$

from the tracking filters selected

3) $\sigma_{Dj} = \sigma^2_{\phi\phi_{ikj}}$

In the above, the subscript D indicates a displayed variable set of σ^2_{Dj} = nearest integer number in cec^2 if $\sigma^2_{Dj} > 9\ cec^2$ then set $= 9\ cec^2$.

p) Status

This display will provide the operator with either information relative to the progress of the synchronization process or information on relative signal strengths from the Burst Phase measurement process.

If still in synchronization

calculate $\Delta C/C_D$ and transmit to C/I

If not then take the Q_m values from a selected frequency and transmit to C/I. Display on a scale of 0-9, i.e., one display digit per station.

3.3.15.4 Outputs

Output	Units	Range	Resolution	Destination
HOLD MRK	Marker	---	---	C-I Routine
COLD START	"	---	---	Combinational Filter
RESET TF	"	---	---	Tracking Filter
STAT MRK_i	"	i=A,B,...H	---	Synchronization, Track Filtering
λ_{pp}, λ_{Di} i-0,1,...,9,PI	deg. & min. N or S	$\|X\| < 180^o$	1/0.1	C-I Panel
L_{pp}, L_{Di} i=0,1,...,9,PI	deg. & min. E or W	$\|X\| < 180^o$	1/0.1	C-I Panel
V_{TAS}, V_C, V_D, V_W	ft/sec	$\|X\| < 1020$	$1020/2^{15}$	C-I Panel
ψ_A, ψ_V, α_D, Ψ_W, ψ_{Di} i=0, 1,...0	degrees	$\|X\| < 360^o$	1	C-I Panel
δP_N, δP_E	ft	6×10^6	1	Comb. Filter
R_{Di} i=0,1,...9	ft	"	1	C-I Panel
DATE	Yr/Mo/Day	$\|X\| \leq 73/12/31$	---	C-I Panel
GMT	hrs/min/sec	$\|X\| \leq 24/60$	1/0.1	C-I Panel
ETE_i	hrs	1×10^3	1	C-I Panel
C_{pos}	$Cycles^2$	Const.	---	Comb. Filter
POSVAR	n miles	$\|X\| < 99$ miles	0.1	C-I Panel
$NCTR_{Dj}$	Counts	$X \leq 99$	1	"
N_{Dj}	"	$X \leq 9$	1	"
σ_{Dj}	cec	$X \leq 9$	1	"
$COH(j_2-j_1)$	cec	$\|X\| \leq 99$	1	"
T_{PI}	hrs	$\|X\| \leq 10^3$	1	"
LOP_{mnj}	cec	$\|X\| < 10^4$	1	"
r_{ij}	unitless	$\|X_{ij}\| < 1$	2^{-31}	Navigation

3.3.16 Built-In Test Programs

The self test of the AN/BRN-7 OMEGA system is predicated upon stored programs which are executed by the computer. These programs are entered automatically in the operational mode, either during power turn-on or during regular intervals. The inputs are self generated and the outputs are the SYSTEM MALF indicator on the Control Indicator, the BITE indicator on the Receiver Computer, and the system malfunction status display on the Control Indicator.

The following tests are entered under executive program control:

a) Basic timing signals test

b) Computer I/O Test

c) CI panel Test (operator initiated only)

d) DMA I/O test*

e) Frequency stability test

f) GP test

g) Memory checksum test

h) Phase angle digital converter test*

i) Phase counter I/O test*

j) Precision Frequency Generator test

k) Program sequence test

l) RF Preamp test*

m) RF section test*

3.3.16.1 RF Section Test

a) General Description: Test signals derived directly from the Precision Frequency Generator (PFG) are coupled directly into the input of each Switching Matrix in a manner identical to the normal (operational) signals. These test signals have a known phase relationship with the PFG. These signals are switched as inputs, under computer control, into the Switching Matrix; the signals are passed through the remaining portions of the receiver in a normal manner and then read by the computer. The incoming data (in the computer) is then compared with known data and verified to be within predetermined tolerances.

b) Test Mechanization: Figure 3.3-12 is a schematic representation of the RF Section Test Mechanization. The Test signals are as follows:

---

* These tests performed at power-on only; all other performed at power-on and iteratively during system operation.

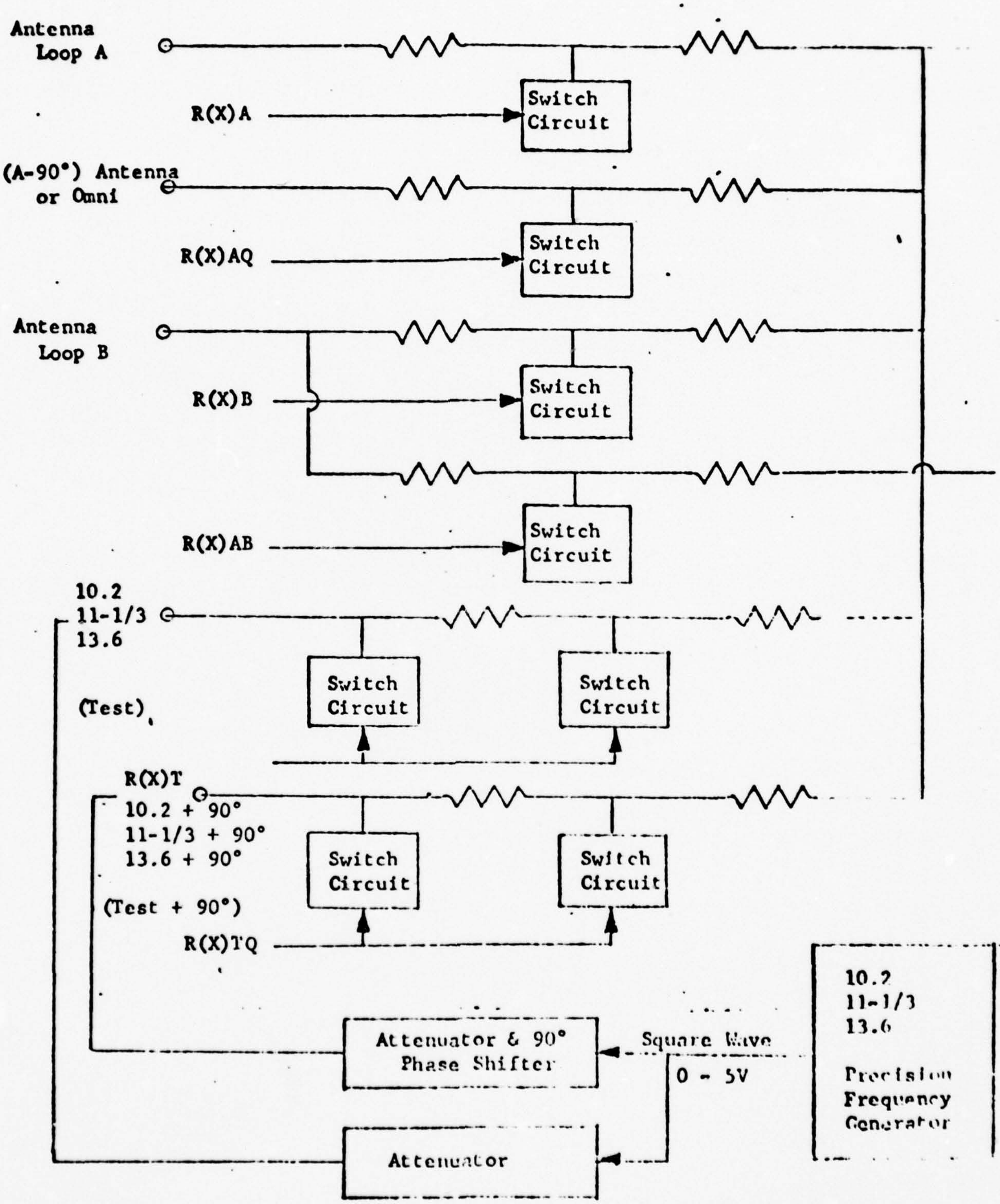


FIGURE 3.3-12 TYPICAL SWITCH MATRIX (THREE REQUIRED)

1) For 10.2 kHz Channel:

Test$_{(c)}$ - 10.2 kHz square wave with a 50% duty cycle. This signal is derived from the 10.2 kHz flip-flop in the PFG, and is attenuated to approximately -65 db prior to insertion into the Switching Matrix. This signal tests the (SINE) non-phase-shifted input characteristics.

Test +90°$_{(c)}$ - 10.2 kHz square wave with a 50% duty cycle. This signal is derived from the 10.2 kHz flip-flop in the PFG, phase shifted by 90° and attenuated to approximately -65 db prior to insertion into the Switching Matrix. This signal tests the (COSINE) phase-shifted input characteristics.

2) For 11-1/3 kHz Channel: Signals are identical to the 10.2 kHz channel except that they are derived from the 11-1/3 kHz flip-flop of the PFG.

3) For 13.6 kHz Channel: Signals are identical to the 10.2 kHz channels except that they are derived from the 13.6 kHz flip-flop of the PFG.

All test signals are under control of computer.

Test	Mnemonic
10.2 Test$_{(c)}$	R10T
10.2 Test +90°$_{(c)}$	R10TQ
11-1/3 Test$_{(c)}$	R11T
11-1/3 Test +90°$_{(c)}$	R11TQ
13.6 Test$_{(c)}$	R13T
13.6 Test +90°$_{(c)}$	R13TQ

c) Software Requirements: The discussion is limited to Receiver Test and Calibrations only and does not define antenna selection requirements.

1) Receiver Test: Test of any given receiver channel is performed at turn-on only. The computer executes the test in the following manner:

a. Switch out all antenna inputs to the channel under test.

b. Switch in the TEST signal (R(X) T = 1).

c. Read and compute the phase (α) of the incoming data after one second.

d. Switch in the TEST +90 signal (R(X) TQ = 1).

e. Read and compute the phase (β) of the incoming data after one second.

f. The test is successful if $67.5° < \alpha - \beta < 112.5°$ for each receiver channel.

2) Receiver Calibration: Calibration of any given receiver channel is performed during any convenient 0.20-second spacing between station bursts. The rate of entry should be approximately 1/5 minute.

For description of calibration equations, refer to Section 3.3.4.

d) Diagnostic Action:

1) Test Select: Entered once at turn-on for receiver test. Calibration is performed every 10 seconds.

2) Test Failure: Failure of any one of these tests indicates that the channel under test is faulty. Failure of all three tests indicates that the fault is most likely in the Receiver I/O section or the Computer I/O section.

3.3.16.2 Computer I/O Test

a) General Description: A conversion, analog-to-digital, is made by the Computer I/O using the computer DC excitation voltages as a reference. The resultant digital value is verified by the computer program.

b) Test Mechanization: Figure 3.3-13 is a schematic representation of the BITE implemented in the I/O section. The test signal consists of the +16VDC and +5VDC signals, and treating this as a normal ac voltage input. Under computer program control, this channel is converted and the resultant value is compared against prestored values in computer memory.

c) Software Requirements: Upon entry into the I/O test, routine addresses the reference channel conversion storage location. (Data is put into memory via DMA). Upon conversion complete, the value is read and compared against prestored value. Failure to compare results in NO-GO situation.

1) Test Select: Program entry is automatic.

2) Timing and Delay: The program tests the input word at a convenient rate not to exceed the DMA input rate of 25/second.

3) Tolerance Value: 486 ± 32 counts (maximum = 1023 counts)

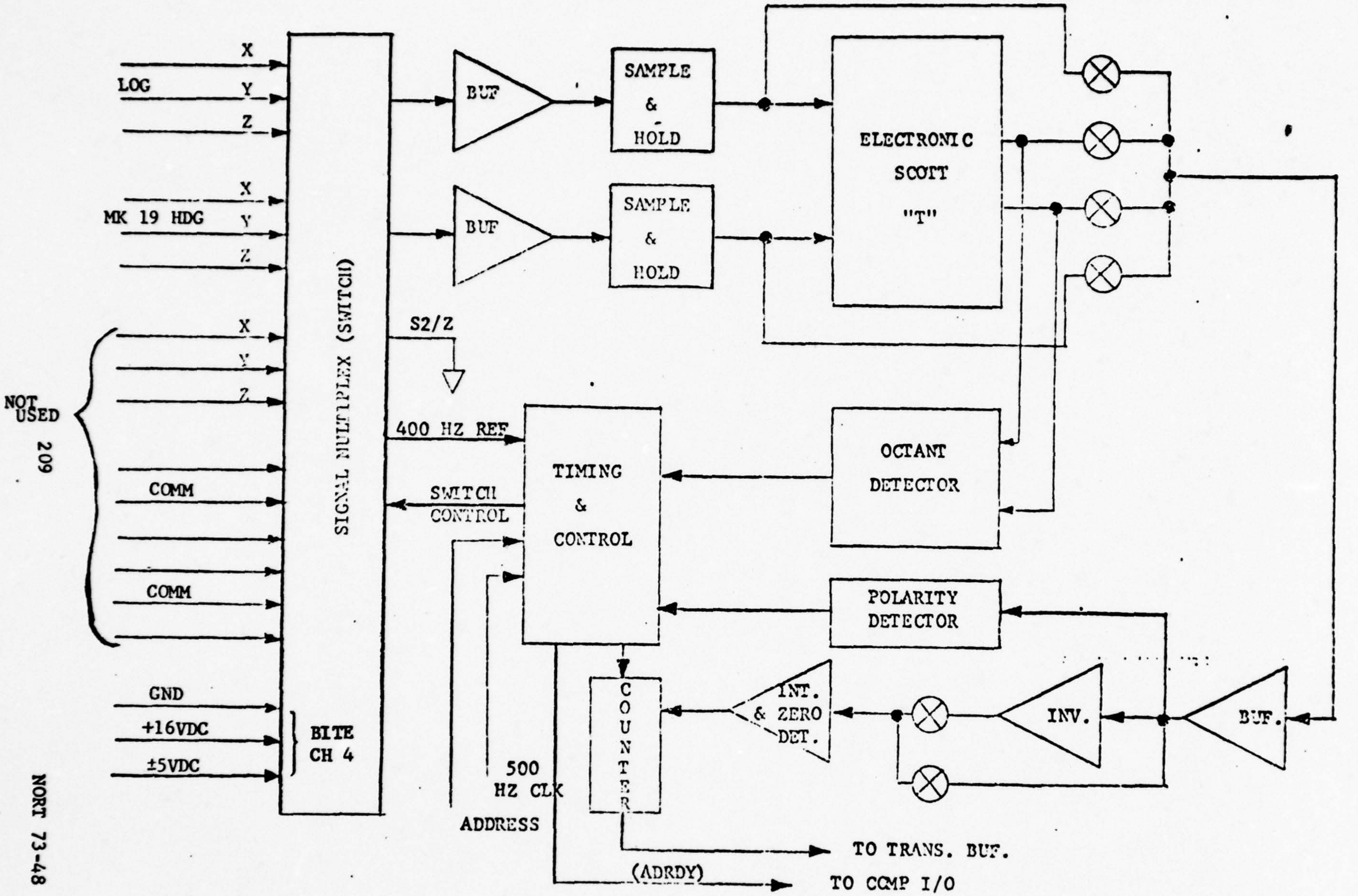


FIGURE 3.3-13 COMPUTER I/O

d) Diagnostic Action:

1) Test Select: Test is under program control and is entered continuously.

2) The test passes whenever the number of individual samples that are out of tolerance is less than three in a set of 12 samples. A failure is indicated if the test has not passed after five sets of data.

3) Test Failure: Failure to convert properly indicates a malfunction of Computer I/O section. However, if the excitation voltage references are absent, test indicates failure.

3.3.16.3 Control-Indicator Panel Test

This test is intended for use as fault isolation between the Receiver-Computer and the C-I panel. It is not intended to fault isolate to subassemblies within the C-I panel.

a) General Description: (C-I Panel is connected in a normal manner to the Receiver-Computer.)

Upon demand of the operator, the computer causes the indicators and segmented displays (lamp filaments) to be turned ON for a period of 10 seconds. This test overrides any other display data and upon completion of the 10-second period the quiescent state is displayed. During the 10-second period the operator must verify that all indicators and segmented displays are ON in the pattern described in the Pre-Cruise Procedure.

NOTE: The communication link between the C-I and Receiver-Computer, for purposes of fault isolation, is considered to be part of the C-I.

b) Test Mechanization: Test is mechanized primarily by computer program. Test is initiated at any time Receiver-Computer is on by depressing PANEL TEST.

c) Software Requirements: The computer program causes all indicators on the C-I panel to be set in a known pattern for a period of 10 seconds for each test request signal from the operator. Upon completion of the 10-second period the panel will return to the quiescent state.

1) Test Select: The operator selects the test by depressing the PANEL TEST button.

2) Test Timing and Delay: The momentary switch data from the C-I panel is available in the DMA table. An interrupt is generated, signaling the computer that a switch has been activated. Upon recognition of the interrupt signal, the program causes all the indicators to be set in the pattern for a period of 10 seconds.

C-I Panel Test Pattern

a) All lamps on (2 seconds) except alphanumeric and segmented displays.

b) Right and left alphanumeric and segmented displays show "starburst" and 888° 8.8.8, respectively, for approximately 2 seconds.

c) All lamps off (2 seconds)

d) Panel in quiescent state; INSERT, CLEAR, DISPLAY, and ET on, and SYSTEM MALF lamp off.

3.3.16.4 Computer Logic Test (GP Test)

a) General Description: The computer Logic Test is designed to verify that the Arithmetic and Control section of the computer hardware is functioning in a normal manner.

The test consists of execution of the basic instructions of the computer being executed and being checked for proper bit patterns in appropriate registers. Upon completion of this a "sample problem" is executed, primarily using the ARCTAN routine of the normal program storage. This routine was selected because it uses about 90% of the instruction repertoire of the computer.

b) Test Mechanization: The test is mechanized entirely within the computer program of the operational routines.

c) Software Requirements:

Timing	Executed once per second.
Test Select	Entry periodically (1/sec)
Test Failure	SYS MALF is turned ON Failure indicates that one of the A&C plug-ins has a failure.

3.3.16.5 Memory Checksum Test

a) General Description: The Memory Checksum Test is provided as a test to verify the contents of computer memory. This test sums all of the permanently stored (non-variable) contents of memory. The computer compares the sum against a predetermined value; failure to compare constitutes a failure of the test.

b) Test Mechanization: This test is mechanized entirely within the computer software. At the time of program assembly, the assembler program generates the "checksum" for that program assembly and places this value in a storage location. When the program is loaded into the Omega computer, this checksum shall be constant for the program as loaded. If memory is altered in any way from the loaded program, the checksum constant is no longer valid and the test will indicate failure.

c) Software Requirements:

1) Assembler Requirement: Generate a checksum and its two's complement for each assembly. This complement to be placed in the assembled program along with the operational storage data.

2) Omega Computer: Upon entry into routine, sum all non-volatile memory, add the two's complement and test for zero. Any non-zero value constitutes a test NO-GO condition. Upon completion of routine, set GO/NO-GO indicator.

a. Test Select: At turn on and runs as background in main program.

b. Test Failure: IF NO-GO condition is indicated, set flag and System Malfunction Indicator. (Receiver-Computer Malfunction indicator set ON.)

(Failure action should be identical for both modes, thus relieving requirement to determine which mode of operation is selected.)

3.3.16.6 Phase Angle/Digital Converter Test

a) General Description: Test signals derived from the +5 volt power source are coupled directly into the chopper circuit of the Phase Angle/Digital Converter. These signals will cause specific values to appear at the output of each converter. The computer then reads these values and compares them against predetermined values to determine a GO/NO-GO condition of the Phase Angle/Digital Converter.

b) Test Mechanization: Figure 3.3-14 is a schematic representation of the test mechanization. The test signal consists of using Computer Logic Level Signal an input to the chopper circuit. The test signal is then processed in a normal manner by the converter. The test signal is switched into all six converter circuits concurrently, unaer computer control.

Signal PDT = Select test input to Phase Angle to Digital Converter. (All channels selected concurrently.)

c) Software Requirements: Test of any given phase converter stage is performed during turn-on only. The computer executes the test in the following manner:

1) Switch in TEST signal (PDT = 1).

NOTE: $\overline{\text{PDT}}$ = 1 means not test mode.

2) Read and compare incoming receiver data against stored constant to verify that the data is within acceptable tolerance limits.

3) Switch out TEST signal (PDT = 0).

a. Test Timing and Display - Samples taken for 1-second duration.

b. Tolerance Values - 1056 ± 544 counts.

d) Diagnostic Action:

1) Test Select: Entered once at turn-on.

2) Test Failure: Failure of test indicates that the Phase Angle to Digital Converter of the selected channel is malfunctioning.

3.3.16.7 Phase Counter I/O Test

a) General Description: This test is designed to check the communication link between the Receiver and the Computer. The test exercises all the functions of the up-down count accumulator buffer and the Direct Memory Access (DMA). When used in conjunction with the I/O - DMA Test, the entire functional link between Receiver and Computer is verified.

The test consists of a seventh (in addition to the six sine/cosine up-down signals) signal signifying count up or count down, which is provided as an input to the Phase Counter. This seventh word is treated in the same manner as the other six from this point on into the computer memory.

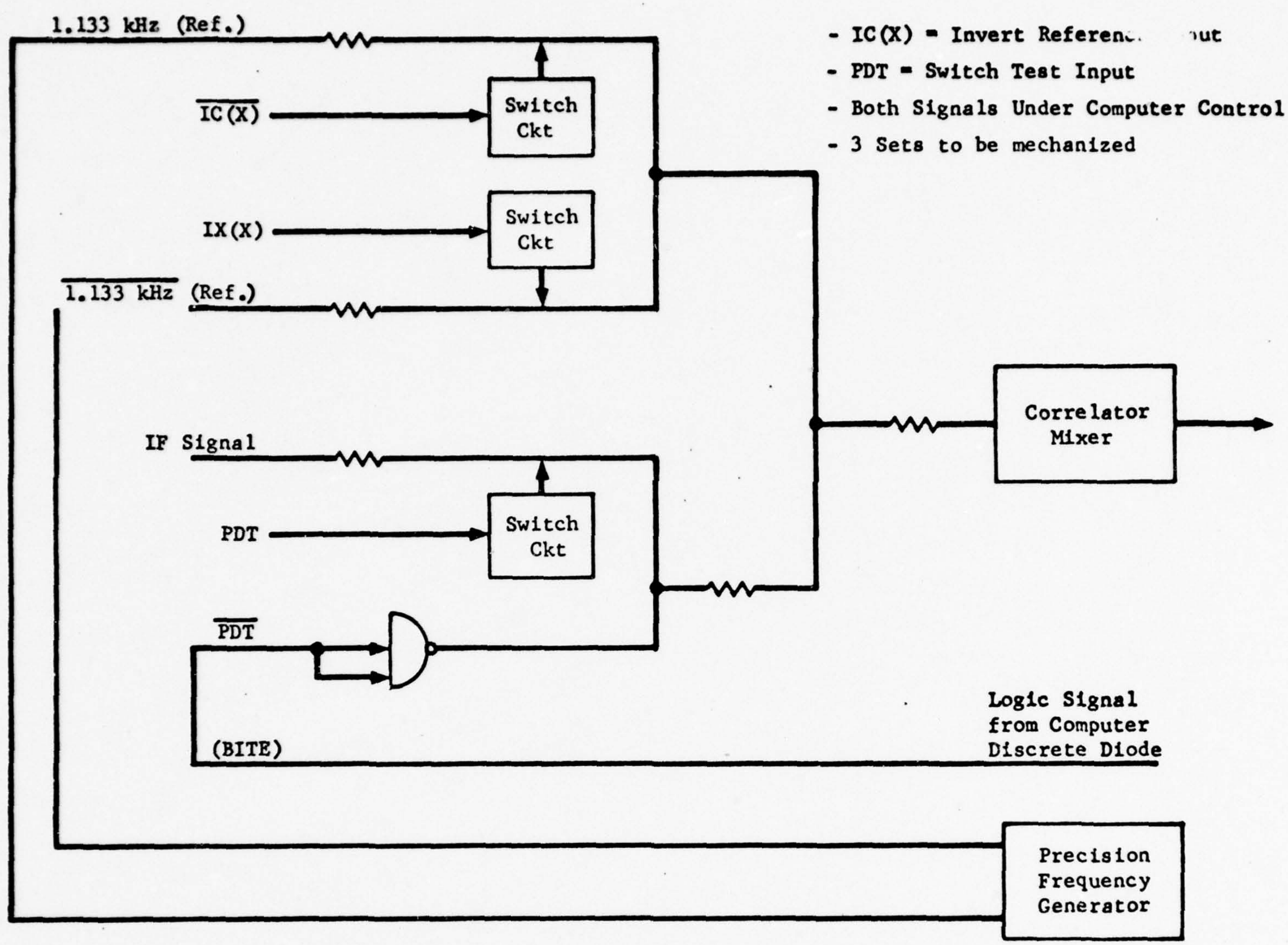


FIGURE 3.3-14 PHASE TO DIGITAL CONVERTER

b) Test Mechanization: Figure 3.3-15 is a schematic representation of the test mechanization. A constant count up-down signal is provided as an input signal to the phase counter by applying a flip-flop output as an input to the phase counter. A true (logic 1) signal signifies count up and a false signal signifies count down.

c) Software Requirements: Program Requirements for this test are:

1) Initialize DMA word 16 to zero

2) Set PHTST = 1 (count up)

3) Wait 1 second, then read and test that input exceeds 400 counts

4) Set PHTST = 0 (count down)

5) Wait 1 second, then read and test.

a. Test Select: Test selected by operational program at turn on.

b. Timing and Delay: Test may be executed only once per 5 milli-second interrupt period.

c. Tolerance: Up count - down counts must be less than ±15 counts. Count per 5 msec = 15, ±1 count.

d) Diagnostic Action: Test is executed at turn-on only. Failure of the test value to compare constitutes a failure in the Receiver I/O section, assuming I/O - DMA test has passed.

3.3.16.8 I/O - Direct Memory Access Test

a) General Description: This test is designed to check the communication link between the receiver and computer. A memory cell location is brought out to the Transfer Buffer via the DMA. The adder control causes the Transfer Buffer to be incremented by the value -1. This incremented value is returned to the original memory cell again via the D or A. where the computer verifies that the cell has been incremented correctly.

The test is initiated under computer program control at turn on.

b) Test Mechanization: Figure 3.3-16 is a schematic representation of the test mechanization. When the test is selected by the computer (RDMAT = 1), a constant -1 value is added to the contents of the DMA word. This is accomplished by switching in a +5 vdc signal at the input to the adder. The test word is brought out from memory, via DMA, and is added to the -1 value, then returned to memory via DMA.

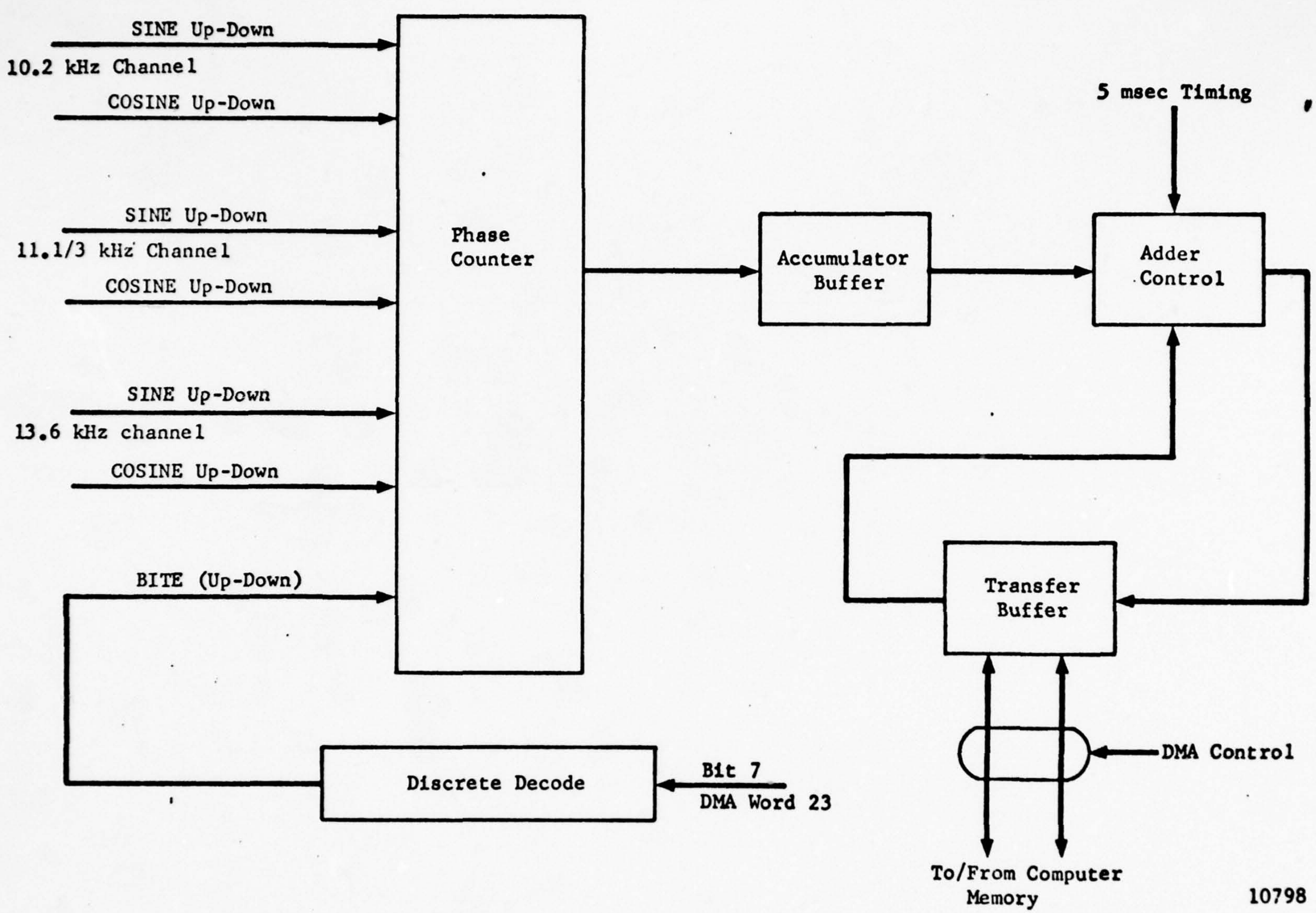


FIGURE 3.3-15 PHASE COUNTER I/O TEST

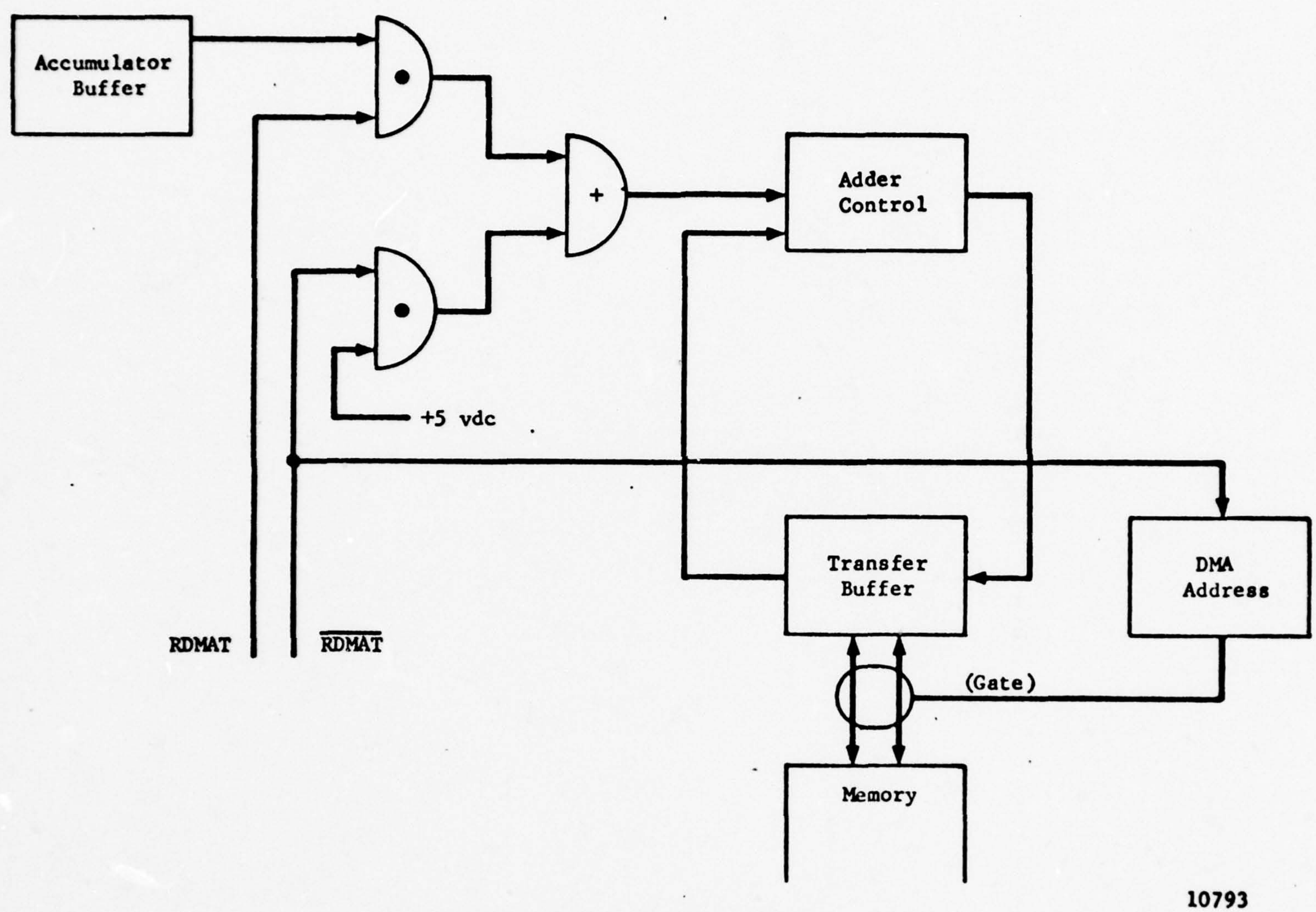


FIGURE 3.3-16 I/O - DMA TEST

c) Software Requirements: The program requirements for this test are:

1) Load DMA word 23 to zero.

2) After one second, set test mode signal (RDMAT) true. (Bit 12 DMA 23 = 1)

3) After the next 5 msec interrupt test DMA word 23 for minus 7 counts.

4) Set GO/NO-GO indicators.

5) Test Select: Bit 12 of DMA word 23 = 1, sets RDMAT true

6) Test Timing and Delay: Test takes two 5 msec interrupts to be completed. Test is selected on the first and verified on the second.

7) Test Failure: Failure of test value to not compare constitutes a failure in the Computer I/O section of the Receiver-Computer.

3.3.16.9 Program Sequence Test

a) General Description: The purpose of this test is to provide a check that the computer pgoram is sequencing instructions and is responding to the basic timing signals from the receiver section. The test consists of a unique discrete output instruction (SET) being given by the computer within a fixed interval of time. The instruction generates a pulse signal which is detected by an integrator type circuit. As long as the circuit continues to be "pulsed" the output of the integrator is high (logic 1) which indicates proper program sequencing. If the program fails to sequence or to respond to the basic OMEGA timing signal (5 msec interrupt), the pulses will not be generated and the output of the integrator will fall (logic 0) indicating a failure.

b) Test Mechanization: Integrator circuit (mechanized in computer I/O) receiver pulses according to the following:

1) Pulse rate 1/100 msec.

2) Pulse width 2 μsec (minimum) and not to exceed 50% of duty cycle.

3) Output shall be high (logic 1) unless duration between pulses is greater than 140 msec.

4) Input pulses to integrator are brought to a pin on test connector of Receiver-Computer.

c) Software Requirements:

1) Program Monitor Pulse signal is generated by a discrete command (SET) at least every 100 msec.

2) Address Code: 000C

d) Diagnostic Action: Failure of program to SET the Monitor Circuit indicates one or more of the following:

1) 5 msec timing and interrupt is not functioning

2) Computer is not sequencing instructions

3) Program is not responding to 5 msec interrupts

Receiver-Computer BITE indicator and SYSTEM MALF are turned on if output of monitor circuit goes to logic 0 state.

3.3.16.10 Computer Timing

a) General Description: The purpose of this test circuit is to provide a monitor of the computer clock and timing section. The output of the computer timing logic is gated into the Program Monitor Circuit every P8 time (50 kHz). In order for the Program Monitor Integrator to function it must receive a P5 and and SET. This test allows a monitor of both the computer timing and program sequencing into a common test circuit. The timing is determined to malfunction if the output is not valid.

b) Software Requirements: None required.

c) Diagnostic Action: Failure of the integrator circuit to maintain a logic 1 level output constitutes a failure of the computer clock and timing.

3.3.16.11 Precision Frequency Generator Test

a) General Description: Included as an integral part of the Precision Frequency Generator (PFG) is a Digital Phase Comparator which will detect an out-of-synchronization condition of the frequency divider network of the PFG. A BITE signal is generated when an out-of-sync condition is detected and is provided to the computer. The computer will sense this condition and generate a re-sync signal. If the out-of-sync condition was due only to a transient condition, the PFG will re-sync upon command of the computer. If the failure is catastrophic, the computer will turn on the appropriate malfunction indicators.

b) Test Mechanization: Figure 3.3-17 is a schematic representation of this test. The sync cycle is 1.76 milliseconds. The reset signal from the computer is a 2 microsecond signal derived from a SET command.

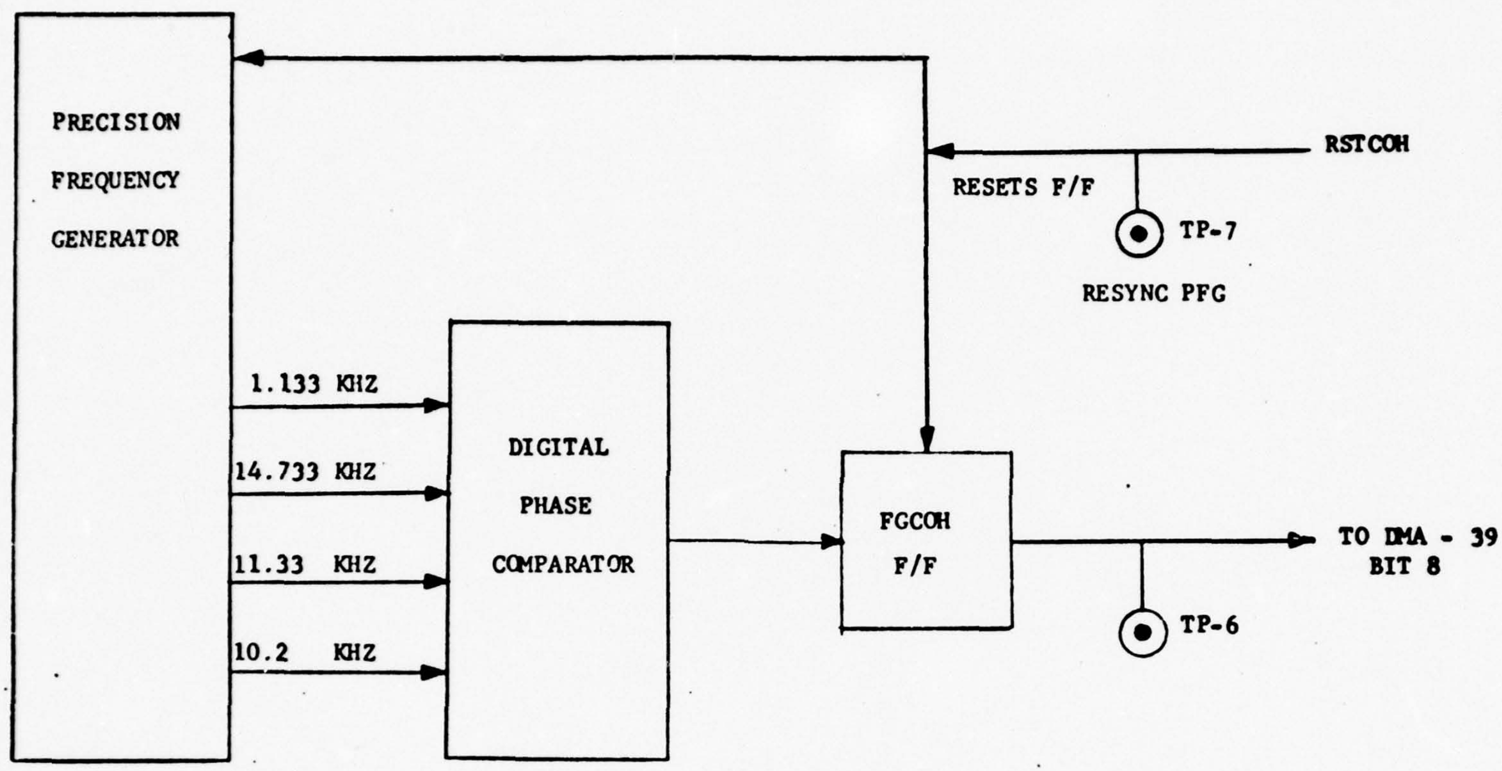


FIGURE 3.3-17 PRECISION FREQUENCY GENERATOR BITE

c) Software Requirements: The program requirements for this test are as follows:

1) Test the PFG BITE signal discrete input at a rate no faster than once per 4 milliseconds.

2) If false no failure exists and return to program.

3) If true give a re-sync command (SET 000A) and restart the system.

d) Diagnostic Action: Repeated (more than 5) setting of the PFG BITE flip-flop constitutes a failure of the PFG and the SYNC indicator at the C/I panel is turned on.

3.3.16.12 RF PreAmp Test

a) General Description: Test signals, derived from the Precision Frequency Generator (PFG) are coupled directly into the input of the two loop amplifiers contained in the Interface Box. These test signals have a known phase relationship with respect to the PFG. These test signals are switched under computer control, into the system; the computer then reads the receiver phase angle and compares this value against a pre-stored value. Any out-of-tolerance condition is defined as a system failure.

b) Test Mechanization: The test signal (EETFA) consists of a 10-1/5 kHz square wave with a 50% duty cycle. The signal will be derived from the 10-1/5 flip-flop of the Precision Frequency Generator which has been attenuated to approximately 3 millivolts peak-to-peak prior to insertion into the test circuitry contained in the Interface Box. The signal is under control of the computer output signal, (EETSA) for Antenna Loop A and Loop B.

c) Software Requirements: The computer shall cause this routine to be entered during initialization (power on).

Test condition is established as follows for complete system test:

1) Select Loop A test input (EETSA = 1 & R10A = 1)

2) Monitor 10-1/5 kHz channel utilizing normal data inputs.

3) Compute Loop A phase and store--arctangent of sine and cosine channels.

4) Select Loop B test input (EETSA = 1 & R10B = 1)

5) Repeat step 2).

6) Compute Loop B phase and store--arctangent of sine and cosine channels.

7) Compute $\Delta\phi = \phi_B - \phi_A$, where $\phi_{A,B}$ are the computed phases from above.

8) Test $|\Delta\phi| \leq 8°$

d) <u>Diagnostic Action</u>:

1) <u>Test Select</u>: Entered once at turn on for system test.

2) <u>Test Failure</u>: Failure of this test is indicated by turning on SYSTEM MALF indicator.

3.3.16.13 Frequency Stability Test

a) <u>General Description</u>: The receiver oscillator frequency variation with respect to the signal frequency provides the oscillator effective time drift. The short term stability of the oscillator is specified as .001 Hz rms averaged for one second. This value of frequency shift provides an effective time drift ($\dot{T}_o$) with respect to the 10.2 kHz Omega signal of approximately 0.1 μ sec/sec.

b) <u>Test Mechanizations</u>: Test is mechanized within the computer program.

c) <u>Software Requirements</u>:

1) Examine $\sigma^2_{\dot{T}_o}$ (variance of $\dot{T}_o$) for < $(.05\,\mu\text{ sec/sec})^2$

2) If variance not less than $(.05\,\mu\text{ sec/sec})^2$ set $\dot{T}_o$ (original value) into the present value and exit test.

3) If variance is less than $(.05\,\mu\text{ sec/sec})^2$, compute $\Delta\dot{T}_o$ which is $|\dot{T}_o \text{ new} - \dot{T}_o \text{ old}|$.

4) If difference ($\Delta\dot{T}_o$) $<.01\,\mu$ sec/sec, exit test; if difference ($\Delta\dot{T}_o$) not $<.01\,\mu$ sec/sec, set oscillator fail marker.

d) <u>Diagnostic Action</u>: Only when test causes fail marker to be set, then the SYSTEM MALF indicator (Control Indicator) and the BITE indicator (Receiver/Computer) are turned on.

3.3.16.14 Miscellaneous

3.3.16.14.1 <u>Direct Memory Access/Test Select</u>: Tables 3.3-8 and 3.3-9 define the DMA word and bit locations for Antenna Select and Test Select.

3.3.16.14.2 <u>Discrete Test Instructions (SET/SNS)</u>: The following are the SET/SNS instructions used for test purposes.

a) Program Monitor	SET
b) Monitor PFG	SNS
c) Resynch PFG	SET

TABLE 3.3-9 TEST SELECT - DMA

MNEMONIC	EETESA	EETESB	PDT	PHTST	(RESERVED FOR A-NEW)	(RESERVED FOR A-NEW)							RDMAT					
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	BIT	TEST FUNCTION SELECT
		0	0	0	X	X	X	X	X	X	X	0	X	X	X	X		
	0		0	0					X	X	X	0	X			X		
	0	0	1	0					X	X	X	0	X			X		PHASE ANGLE TO DIGITAL CONVERTER TEST
	0	0	0	1					X	X	X	0	X			X		PHASE COUNTER I/O TEST
	0	0	0	0					X	X	X	1	X			X		INPUT/OUTPUT - DMA TEST
	X	X	X	X					0	X	X	X	X			X		REC/COMP NO-GO (REC/COMP MALF INDICATOR/AUGMENTER)
	X	X	X	X					X	0	X	X	X			X		SYSTEM MALFUNCTION (PROG CONTROL NO-GO)
	X	X	X	X					X	X	X	X	1			X		ALLOW I/O INTERRUPT (5 MSEC AND C-I PANEL)
	X	X	X	X					X	X	X	X	X			1		REMOTE C-I SELECT
	0	0	0	0					0	0	0	0	0			0		(RESERVED FOR ANTENNA COUPLER MALFUNCTION INDICATOR)
	X	X	X	X					X	X	X	X	X			X		
	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		

DMA Word - 23 - Test Select

Bits 1 → 8 used for Receiver Tests
Bits 9 → 16 used for Computer Discrete I/O

TABLE 3.3-10 ANTENNA SELECT - DMA

R(X)A	R(X)AQ	R(X)B	R(X)AB	R(X)TQ	R(X)T	IC(X)	(SPARE)									← MNEMONIC	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	BIT	ANTENNA FUNCTION SELECT
0	0	0	0	0	0	0	X										RECEIVER FRONT END OPEN
1	0	0	0	0	0	0											ANTENNA LOOP A → CHANNEL (X) (SEE NOTE)
0	1	0	0	0	0	0											ANTENNA LOOP A - 90° → CHANNEL (X)
0	0	1	0	0	0	0											ANTENNA LOOP B → CHANNEL (X)
0	0	0	1	0	0	0											ANTENNA LOOP B → CHANNEL (X)
0	0	0	0	1	0	0											CALIBRATE/TEST (INVERTED) → CHANNEL (X)
0	0	0	0	0	1	0											CALIBRATE/TEST → CHANNEL (X)
1	0	1	0	0	0	0											ANTENNA LOOP (A + B) → CHANNEL (X)
1	0	0	1	0	0	0											ANTENNA LOOP (A - B) → CHANNEL (X)
1	0	0	1	0	0	1											ANTENNA LOOP (B - A) → CHANNEL (X)
							X										

DMA Word - 20 10.2 kHz Channel
DMA Word - 21 11-1/3 kHz Channel
DMA Word - 22 13.6 kHz Channel

Bits 9 → 16 Not Used.

NOTE: Loop A must be selected when using Floater Antenna.

3.3.17 Built-In-Test Equipment

In addition to the Built-In-Test Programs discussed in Paragraph 3.3.16, specific hardware is added to those portions of the Receiver-Computer which cannot be tested by computer programs. Primarily these monitoring circuits are located in the Computer and Power Supply sections.

Figures 3.3-18, -19 and -20 are schematic representations of the BITE.

3.3.17.1 Malfunction Indicators.

3.3.17.1.1 System Level: The Malfunction Indicator located on the Control-Indicator signifies a system malfunction. This includes inability to detect and/or process OMEGA signals as well as any detectable hardware malfunction. Indicator remains active only during time fault or malfunction is current.

3.3.17.2 Maintenance Level: The Receiver-Computer has a Malfunction Indicator which, once set on by the Built-In-Test, will remain set until reset by the maintenance operator. The Antenna Coupler, which in a general installation is not visible, will not have a separate BITE indicator.

In addition the Receiver-Computer will have a separate indicator which, if the power supply fails, will be lighted as long as the System ON/OFF switch is in the ON position.

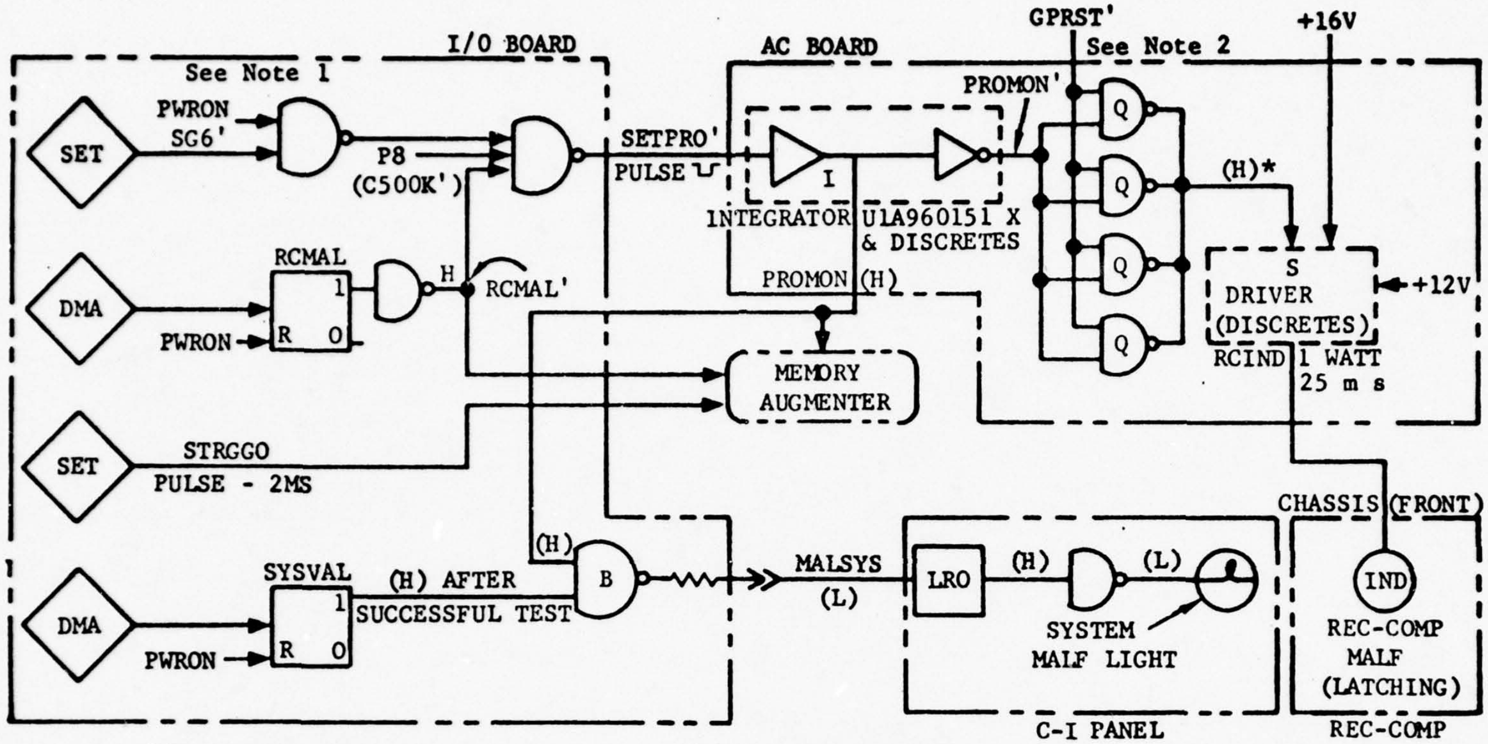
3.3.17.2 Description of BITE

The following describes the BITE for:

- Power Supply
- Program Sequencing and/or
- Computer Timing Circuitry

3.3.17.2.1 Power Supply BITE: The BITE associated with the Power Supply consists of level detectors on each of the six Power Supply outputs. The outputs of the level detectors are fed to an "AND" gate. The output of this "AND" gate will remain high as long as the Power Supply outputs remain within the tolerance limits. The output of the gate will go to ground level in the event of a failure. This signal will then be used to turn off the Power Supply to prevent further damage to the assembly.

The Power Supply Malfunction Indicator will be lighted for any Power Supply malfunction and will remain lighted until the System ON/OFF select switch is returned to the power OFF position.



(H) = NORMALLY HIGH (L) = NORMALLY LOW

(H) * MUST BE HIGH WHILE +16 VOLTS IS ON UNLESS MALFUNCTION OCCURS

NOTES: 1. (PWRON)' "OR"ED WITH SET INSTRUCTION SO THAT THE INTEGRATOR WILL RECEIVE PULSES DURING INITIALIZATION (GPRST). THE FIRST SET INSTRUCTION IS NOT NEEDED UNTIL 80 ms AFTER COMPUTER START.

2. (GPRST')' IS "OR"ED WITH INTEGRATOR OUTPUT TO PREVENT FALSE SIGNAL DURING 27 MSEC AFTER +16 VOLTS IS TURNED ON BUT CLOCK IS NOT GUARANTEED TO BE OPERATING.

10794

FIGURE 3.3-18 SELF-TEST BITE IN THE I/O

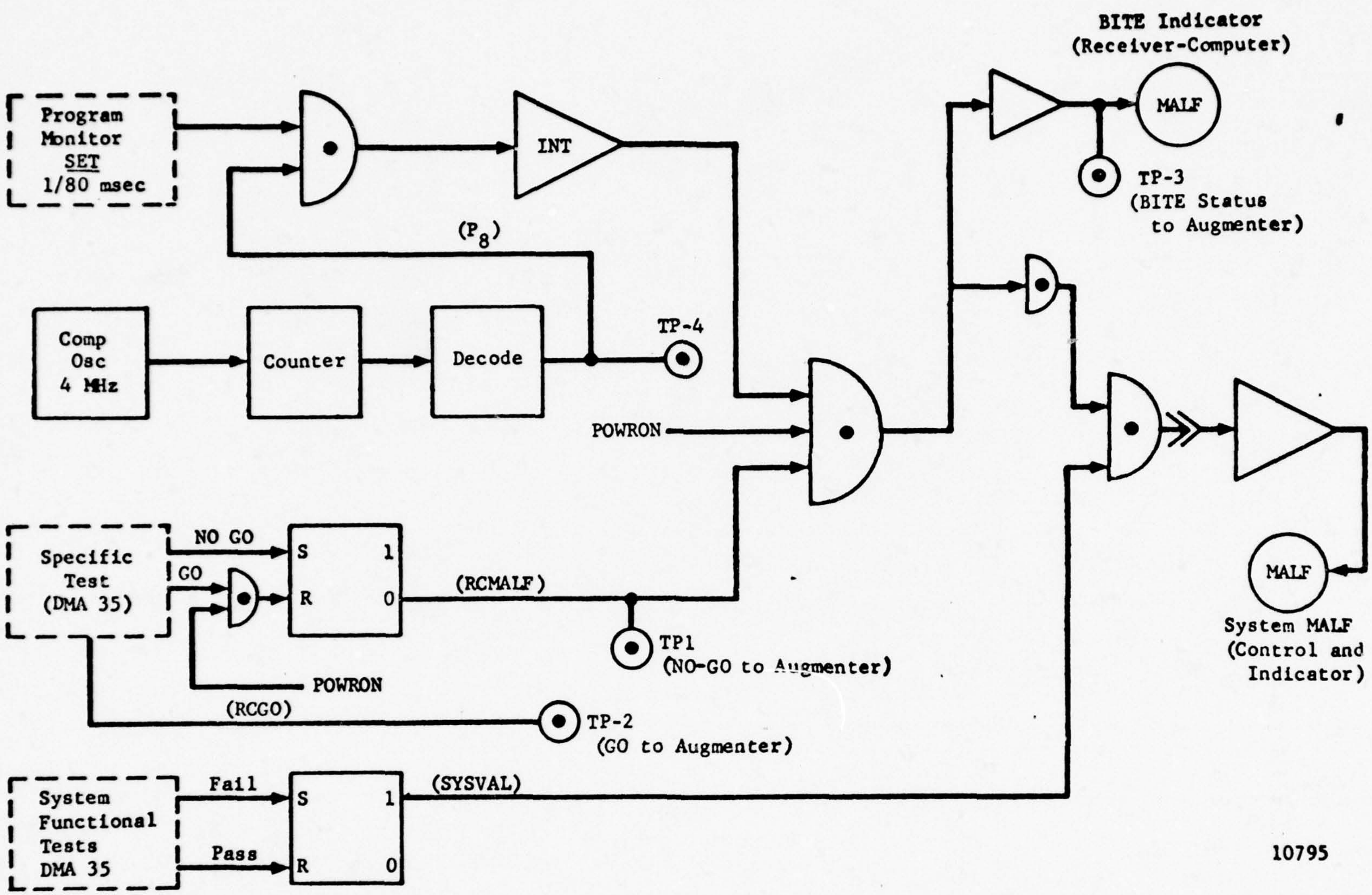
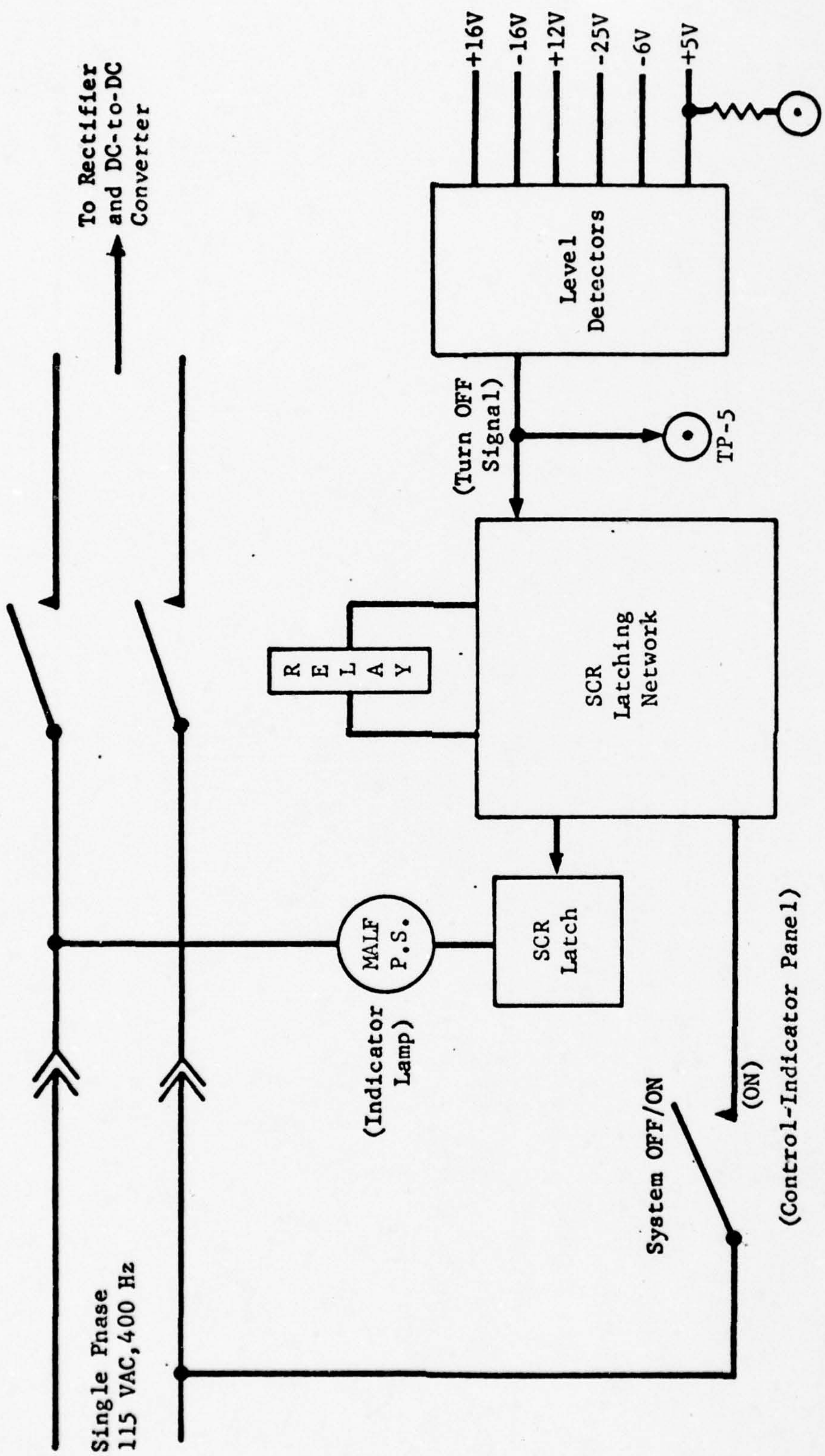


FIGURE 3-3-19 COMPUTER/SYSTEM BITE



NOTE: Each power supply voltage will be brought out to test connector through a resistor.

10796

FIGURE 3.3-20 POWER SUPPLY BITE

3.4 ADAPTATION

3.4.1 General Environment

There are no computer program characteristics peculiar to particular installation of the Submarine OMEGA Navigation System.

3.4.2 System Parameters

There are no system parameters that are subject to change due to operational variations.

3.4.3 System Capacities

The OMEGA system has the capacity to handle eight broadcasting stations although at present it handles four only. It will accommodate the navigational functions for ten fixed destinations and one moving destination (refer to Section 3.3.15, Control-Indicator, for specifics).

APPENDIX A

MATHEMATICAL ANALYSIS

A.1 DERIVATION OF THE TRACKING FILTERS

The following derivation of a tracking filter is based on a rho-rho navigation concept in that the derivation assumes that the quantity to be tracked is the station-receiver phase measurements. The Submarine OMEGA Navigation System uses the same tracking filter except that the quantity being tracked is the station-to-station phase difference to be used in the hyperbolic mode of navigation. The tracking filter derivation presented here applies to both concepts, but was originally derived for rho-rho mechanization, and presented at the symposium on Nonlinear Estimation Theory and Its Application, held at the University of California at San Diego in September 1970.

A.2 TRACKING FILTER DESCRIPTION

As previously mentioned, a given OMEGA transmitting station transmits on a given frequency once every 10 seconds. The duration of the transmission burst is about one second, the precise length varying both with transmitting station and with frequency. The OMEGA receiver must determine the phase of this signal relative to a local oscillator voltage at the same frequency. Because OMEGA is a world-wide system with coverage obtained from eight stations, the receiver is expected to be able to operate at a signal-to-noise ratio of -20 db measured over a 100-cycle bandwidth. Thus any single one-second phase measurement may be inaccurate. It then becomes necessary to average successive phase measurements spaced 10 seconds apart in time. The propagation velocity over a given path is steady enough over a period of several minutes to allow this averaging to be done. However, the effect of craft motion must be accounted for. The component of craft velocity in the direction of the transmitter produces a phase rate. This phase rate must be accounted for in averaging successive phase measurements. Also a small difference in frequency between the local oscillator and the transmitter produces a phase rate. It is the job of the tracking filter to filter or average successive phase measurements taking account of phase rate.

A separate tracking filter is used for each of the three frequencies from each of the eight transmitting stations. Thus there are a total of twenty-four tracking filters in the receiver. Each of these tracking filters operates independently, even though there are relationships among the three frequencies from a given station with regard to phase rate.

If a velocity reference is available on the craft, the velocity information can be used to help the tracking filter determine phase rate. However, a velocity reference is not necessary for tracking filter operation. The

tracking filter can use successive values of phase which are separated by an accurately known time of ten seconds to determine a phase rate as well as a value of phase. However, if phase rate is not constant (for example if the craft turned) this becomes a difficult task. The tracking filter must be able to operate through changes in phase rate.

The tracking filter described in this approach for an OMEGA navigation set estimates the following two quantities:

1) Current value of phase

2) Phase rate error.

The phase rate error is the error in the velocity reference if rate aiding is used or is the total velocity component from craft to target if no rate aiding is used. The phase rate error also includes the effect of a small frequency difference between the local oscillator and the transmitter. The current value of phase is the value half way through the nominally one second transmission burst interval.

In making estimates of phase the filter must average the value of the current phase measurement with that determined from all previous measurements. One common way to accomplish this averaging is to apply a fixed weighting; for example, one tenth the new value plus nine tenths of the old value. A minimum variance estimate can be developed by weighting the current phase measurement and the value based upon previous phase measurements inversely as their variances. To apply a minimum variance technique requires that a variance of the phase measurement error be available. The variance of a single phase measurement is dependent upon the instantaneous signal-to-noise ratio. Thus in order to develop a minimum variance phase estimate one must have knowledge of the signal-to-noise ratio.

The phase of the received signal relative to the local oscillator is a quantity which is modulus 2π radians. Values are considered to lie in the range $-\pi$ radians to $+\pi$ radians. (Equivalently values are between ±180° or ±.5 cycles or ±50 CEC.) Consider the problem of estimating the true value of an angle modulus 2π given a number of samples. A simple arithmetic average of the sample values φ_i

$$\hat{\varphi} = \frac{1}{n} \sum_{i=1}^{n} \varphi_i$$

does not yield an unbiased estimation under low signal-to-noise conditions. To obtain an unbiased estimator of phase modulus 2π one can use the following algorithm:

$$\sin \hat{\varphi} = \frac{1}{n} \sum_{i=1}^{n} \sin \varphi_i$$

$$\cos \hat{\varphi} = \frac{1}{n} \sum_{i=1}^{n} \cos \varphi_i$$

$$\hat{\varphi} = \tan^{-1} \left[\sin \hat{\varphi} / \cos \hat{\varphi} \right]$$

One finds the average of the sines and cosines of the sample values and takes the arc tangent of the ratio of the averages. This is equivalent to representing each sample phase angle as a unit vector, averaging the vector components, and then finding the angle of the resultant vector formed by the component averages.

In order that the tracking filter develop an unbiased, minimum-variance estimate of phase, the phase measurement inputs should be quantities proportional to the sine and cosine of measured phase along with a variance for the phase measurement error. It is precisely these quantities which are developed in the burst filter.

The output of the IF consists of a sine wave beat down to 1133 1/3 Hz imbedded in noise. This IF output is multiplied by both a local oscillator signal and this local oscillator signal shifted by 90°. These two products are integrated over the nominally one second burst period. The integrator outputs are then proportional to the sine and cosine of the phase angle between the IF output and the local oscillator. Call the integrator outputs X_s and X_c. Another quantity is computed in the burst filter:

$$Q = X_c^2 + X_s^2$$

This quantity Q is also computed in between burst times and called Q_t. Q_t is computed from integrator outputs formed by processing the noise present during the .2 second interval between bursts in the same way as the signal plus noise is processed during the burst time. From the quantities Q and Q_t the burst filter computes an estimate of the variance of the phase measurement error.

These burst filter outputs become the inputs to the tracking filters. The tracking filters are designed to be minimum variance vector filters. Thus the tracking filters must generate an estimate of the variance of the error in estimating the phase angle based upon the average of the previous phase inputs from the burst filter. The tracking filter also generates the variance of phase rate error and the covariance between phase and phase rate

error. The variance computations will be found to be dependent upon the value of the cosine of the difference between the phase measurement from the burst filter and the tracking filter estimate of phase based upon previous burst filter measurements. When the phase measurement and the phase estimate disagree, the variances will tend to increase, provided the variance of the phase measurement is not too much larger than the variance of the phase estimate. This property of variance increase with disagreement between measured and predicted phase is a desirable quality.

Consider the following situation:

1) The tracking filter has been tracking for some time
2) There is no rate aiding. Thus phase rate error is the total phase rate.
3) The craft makes a turn such that the phase rate makes a quick change.

The tracking filter is then required to make a new estimate of phase rate. The variance on phase rate (and on phase) must increase to allow the successive phase measurements to have an effect upon estimating the new value of phase rate. This adaptive process of increasing the variances when the phase measurement and the phase estimate disagree keeps the filter from becoming so sure of its estimate that it ignores input data when the conditions change. It also keeps the phase estimate from diverging from the true value of received phase.

This tracking filter approach for an OMEGA navigation set can be considered an adaptive, vector filter.

A.3 DERIVATION OF THE TIME UPDATE EQUATIONS

Before deriving the tracking filter equations the symbol definitions will be stated. Let phase mean the value of phase received from the OMEGA transmitting station relative to the local oscillator. Then let

$\varphi_T(n) \equiv$ true value of phase at the time of the nth iteration

$\varphi_m(n) \equiv$ measured value of phase at the time of the nth iteration

$\Delta\varphi_m(n) \equiv \varphi_T(n) - \varphi_m(n) \equiv$ error in the phase measurement at the time of the nth iteration

$\hat{\varphi}(i,j) \equiv$ estimate of phase at the time of the ith measurement based upon j measurements ($j=i$ or $j=i-1$)

$\Delta\varphi(i,j) \equiv \varphi_T(i) - \hat{\varphi}(i,j) \equiv$ error in estimating phase at the time of ith measurement based upon j measurements

$\hat{\Delta\varphi}(i,j) \equiv$ estimate of $\Delta\varphi(i,j)$

$\dot{\varphi}_T(n) \equiv$ true value of phase rate during the interval between the n-1 and

nth iteration (Actually $\frac{1}{\Delta t} \int_{t_{n-1}}^{t_n} \dot{\varphi}_T(t)\, dt$)

$\dot{\varphi}_{DR}(n) \equiv$ phase rate as measured by the velocity aiding source (dead reckoning (DR) velocity) during the interval between the n-1 and

nth iteration (Actually $\frac{1}{\Delta t} \int_{t_{n-1}}^{t_n} \dot{\varphi}_{DR}(t)\, dt$)

$\Delta\dot{\varphi}(n) \equiv \dot{\varphi}_T(n) - \dot{\varphi}_{DR}(n) \equiv$ error in $\dot{\varphi}_{DR}(n)$

$\hat{\Delta\dot{\varphi}}(i,j) \equiv$ estimate of $\Delta\dot{\varphi}$ (i) based upon j measurements (j=i or j=i-1)

$\Delta t \equiv$ time between iterations.

Now from the definitions

$$\varphi_T(n) = \varphi_T(n-1) + \dot{\varphi}_T(n)\, \Delta t \tag{1}$$

The tracking filter time updates its estimate of phase using an analogous equation.

$$\hat{\varphi}(n,n-1) = \hat{\varphi}(n-1,\ n-1) + \left[\dot{\varphi}_{DR}(n) + \hat{\Delta\dot{\varphi}}(n-1,n-1)\right] \Delta t \tag{2}$$

The tracking filter estimate of phase rate error is carried as a quantity $\left[\hat{\Delta\dot{\varphi}}\ \Delta t\right]$ converting it to an angular error developed over a time Δt as a result of an error in phase rate $\hat{\Delta\dot{\varphi}}$. The time update is simply

$$\hat{\Delta\dot{\varphi}}(n,n-1)\, \Delta t = \hat{\Delta\dot{\varphi}}(n-1,n-1)\, \Delta t \tag{3}$$

Equations (2) and (3) are the time update equations for the state variables φ and $\Delta\dot{\varphi}\ \Delta t$ of the tracking filter.

Subtracting (2) from (1) and using the definitions

$$\Delta\varphi(n,n-1) = \Delta\varphi(n-1,n-1) + \left[\Delta\dot{\varphi}(n) - \hat{\Delta\dot{\varphi}}(n-1,n-1)\right] \Delta t \tag{4}$$

Assume the following expression is true:

$$\Delta\dot{\varphi}(n) = \Delta\dot{\varphi}(n-1) \tag{5}$$

This assumption for constant phase rate error will be modified presently.

Let

$$\sigma^2_{\varphi\varphi}(i,j) \equiv E\left[\varphi_T(i) - \hat{\varphi}(i,j)\right]^2 = E\left[\Delta\varphi(i,j)\right]^2 \tag{6}$$

$$\sigma^2_{\dot{\varphi}\dot{\varphi}}(i,j) \equiv E\left\{\left[\Delta\dot{\varphi}(i) - \widehat{\Delta\dot{\varphi}}(i,j)\right]\Delta t\right\}^2 \tag{7}$$

$$\sigma^2_{\varphi\dot{\varphi}}(i,j) \equiv E\left\{\Delta\varphi(i,j)\left[\Delta\dot{\varphi}(i) - \widehat{\Delta\dot{\varphi}}(i,j)\right]\Delta t\right\} \tag{8}$$

where E indicates the expected value.

From equations (3), (5), and (7)

$$\sigma^2_{\dot{\varphi}\dot{\varphi}}(n,n-1) = E\left\{\left[\Delta\dot{\varphi}(n-1) - \Delta\dot{\varphi}(n-1,n-1)\right]\Delta t\right\}^2 = \sigma^2_{\dot{\varphi}\dot{\varphi}}(n-1,n-1) \tag{9}$$

From equations (3) through (8)

$$\sigma^2_{\varphi\varphi}(n,n-1) = E\left\{\Delta\varphi(n-1,n-1) + \left[\Delta\dot{\varphi}(n-1) - \widehat{\Delta\dot{\varphi}}(n-1,\ n-1)\right]\Delta t\right\}^2$$

$$= \sigma^2_{\varphi\varphi}(n-1,n-1) + 2\sigma^2_{\varphi\dot{\varphi}}(n-1,n-1) + \sigma^2_{\dot{\varphi}\dot{\varphi}}(n-1,n-1) \tag{10}$$

From equations (3), (4), (5), (7), and (8)

$$\sigma^2_{\varphi\dot{\varphi}}(n,n-1) = E\left\{\left[\Delta\varphi(n-1,n-1) + (\Delta\dot{\varphi}(n) - \widehat{\Delta\dot{\varphi}}(n-1,n-1))\Delta t\right]\right.$$

$$\left.\left[\Delta\dot{\varphi}(n) - \widehat{\Delta\dot{\varphi}}(n,n-1)\right]\Delta t\right\}$$

$$= E\left\{\left[\Delta\varphi(n-1,n-1) + (\Delta\dot{\varphi}(n-1) - \Delta\dot{\varphi}(n-1,n-1))\Delta t\right]\right.$$

$$\left.\left[\Delta\dot{\varphi}(n-1) - \widehat{\Delta\dot{\varphi}}(n-1,n-1)\right]\Delta t\right\}$$

$$= \sigma^2_{\varphi\dot{\varphi}}(n-1,n-1) + \sigma^2_{\dot{\varphi}\dot{\varphi}}(n-1,n-1) \tag{11}$$

The assumption stated in equation (5) will now be considered. The equation implies that the error in the velocity source is a constant from interval to interval from the time the tracking filter begins filtering until the output is read by the combinational filter and the tracking filter is reset. This assumption does not account for the noise in the velocity source. Furthermore if no velocity reference is available, the phase rate error $\Delta\dot{\varphi}$ is the total phase velocity. In this case equation (5) states

that the phase velocity itself is constant. To mitigate this assumption equation (9) is modified to

$$\sigma^2_{\dot{\varphi}\dot{\varphi}}(n,n-1) = \sigma^2_{\dot{\varphi}\dot{\varphi}}(n-1,n-1) + r^2(n) \tag{12}$$

The additive r^2 term accounts for the uncertainty in the constancy of $\Delta\dot{\varphi}$. The variance in phase rate error is increased in the time update process.

Equations (10), (11), and (12) are the time update equations for the tracking filter covariance matrix.

A.4 DERIVATION OF THE MEASUREMENT UPDATE EQUATIONS

Before directly deriving the measurement update equations for the tracking filter a general phase estimation problem will be considered. Given two noisy measurements of a phase angle modulo 2 π along with their variances, determine a best estimate of phase and the variance of the estimate. In a previous section it was stated that an unbiased estimate could be formed by taking the sines and cosines of the measurements, averaging these, and taking the arc-tangent of the average. Calling the two measurements θ_1 and θ_2 and the estimate u

$$\tan u = \frac{\sin \theta_1 + F \sin \theta_2}{\cos \theta_1 + F \cos \theta_2} = \frac{y}{x} \tag{13}$$

where F is the weighting factor to be determined to yield a minimum variance estimate. From (13) we can say

$$\sin u = y\ (x^2 + y^2)^{-1/2} \tag{14}$$

$$\cos u = x\ (x^2 + y^2)^{-1/2} \tag{15}$$

$$u = \tan^{-1} \frac{y}{x} \tag{16}$$

Then differentiating (16)

$$\Delta u = \frac{1}{1 + (y/x)^2}\ \Delta(y/x) = \frac{x\Delta y - y\Delta x}{x^2 + y^2} = \frac{\cos u\ \Delta y - \sin u\ \Delta x}{(x^2 + y^2)^{1/2}} \tag{17}$$

Now let

$$\sigma_u^2 = E\left[\Delta u^2\right] \tag{18a}$$

$$\sigma_x^2 = E\left[\Delta x^2\right] \tag{18b}$$

$$\sigma_y^2 = E\left[\Delta y^2\right] \tag{18c}$$

$$\sigma_{xy}^2 = E\left[(\Delta x)(\Delta y)\right] \tag{18d}$$

where E indicates the expected value.

Then from squaring (17), taking expected values, and using (18)

$$\sigma_u^2 = \frac{\cos^2 u\,\sigma_y^2 + \sin^2 u\,\sigma_x^2 - 2\sin u\cos u\,\sigma_{xy}^2}{x^2 + y^2} \tag{19}$$

We wish to express σ_u^2 in terms of θ_1 and θ_2 instead of x and y. Differentiating (13)

$$\Delta y = \cos\theta_1\,\Delta\theta_1 + F\cos\theta_2\,\Delta\theta_2 \tag{20}$$

$$\Delta x = -\sin\theta_1\,\Delta\theta_1 - F\sin\theta_2\,\Delta\theta_2 \tag{21}$$

Then from (20) and (21)

$$\sigma_y^2 = \cos^2\theta_1\,\sigma_1^2 + F^2\cos^2\theta_2\,\sigma_2^2 + 2F\cos\theta_1\cos\theta_2\,\sigma_{12}^2 \tag{22}$$

$$\sigma_x^2 = \sin^2\theta_1\,\sigma_1^2 + F^2\sin^2\theta_2\,\sigma_2^2 + 2F\sin\theta_1\sin\theta_2\,\sigma_{12}^2 \tag{23}$$

$$\sigma_{xy}^2 = -\sin\theta_1\cos\theta_1\,\sigma_1^2 - F^2\sin\theta_2\cos\theta_2\,\sigma_2^2 - F\sin(\theta_1+\theta_2)\,\sigma_{12}^2 \tag{24}$$

where

$$\sigma_1^2 = E\left[\Delta\theta_1^2\right] \tag{25a}$$

$$\sigma_2^2 = E\left[\Delta\theta_2^2\right] \tag{25b}$$

$$\sigma_{12}^2 = E\left[(\Delta\theta_1)(\Delta\theta_2)\right] \tag{25c}$$

Also

$$x^2 + y^2 = 1 + F^2 + 2F \cos (\theta_1 - \theta_2) \tag{26}$$

Then substituting (22), (23), (24), and (26) into (19) and doing some simplifying algebra one arrives at

$$\sigma_u^2 = \Big[\cos^2 (u-\theta_1)\, \sigma_1^2 + F^2 \cos^2 (u-\theta_2)\, \sigma_2^2 + 2F \cos (u-\theta_1) \cos (u-\theta_2)\, \sigma_{12}^2\Big]\Big[1 + F^2 + 2F \cos (\theta_1-\theta_2)\Big]^{-1} \tag{27}$$

To express σ_u^2 in terms of θ_1, θ_2, and F, one can expand the expressions for $\cos (u-\theta_1)$ and $\cos (u-\theta_2)$ and use (14), (15), and (26) to obtain

$$\cos (u-\theta_1) = \frac{1 + F \cos (\theta_2-\theta_1)}{\left[1 + F^2 + 2F \cos (\theta_2 - \theta_1)\right]^{1/2}} \tag{28}$$

$$\cos (u-\theta_2) = \frac{F + \cos (\theta_2-\theta_1)}{\left[1 + F^2 + 2F \cos (\theta_2 - \theta_1)\right]^{1/2}} \tag{29}$$

Then (27) becomes

$$\sigma_u^2 = \left\{\left[1 + F\cos(\theta_2 - \theta_1)\right]^2 \sigma_1^2 + F^2\left[F + \cos(\theta_2 - \theta_1)\right]^2 \sigma_2^2\right.$$

$$\left. + 2F\left[1 + F\cos(\theta_2 - \theta_1)\right]\left[F + \cos(\theta_2 - \theta_1)\right]\sigma_{12}^2\right\}$$

$$\left[1 + F^2 + 2F\cos(\theta_2 - \theta_1)\right]^{-2}$$

$$= \left[(1 + FC_{12})^2 \sigma_1^2 + F^2 (F + C_{12})^2 \sigma_2^2\right.$$

$$\left. + 2F(1 + FC_{12})(F + C_{12})\sigma_{12}^2\right]\left[1 + F^2 + 2FC_{12}\right]^{-2} \qquad (30)$$

where $$C_{12} = \cos(\theta_2 - \theta_1) \qquad (31)$$

To find the minimum variance estimator for u one must find the value of F which minimizes σ_u^2. To do this one can differentiate equation (30) with respect to F and set the derivative equal to zero. The resulting expression is quite long but after considerable algebraic manipulation simplifies to the following equation

$$\frac{\partial\sigma_u^2}{\partial F} = 0 = -\left[1 + FC_{12}\right]\left[C_{12} + 2F + F^2 C_{12}\right]\sigma_1^2$$

$$+ F\left[F + C_{12}\right]\left[C_{12} + 2F + F^2 C_{12}\right]\sigma_2^2$$

$$+ \left[C_{12} + 2F - 2F^3 - F^4 C_{12}\right]\sigma_{12}^2 \qquad (32)$$

This is a fourth order equation in F. To mechanize a solution for F from this equation in the tracking filter would be quite complex. However, an approximate value for F can be generated. This value becomes exact as $C_{12} \to 1$ or the two estimates θ_1 and θ_2 are nearly alike. This approximation has proved to be satisfactory in practice. Setting $C_{12} = 1$ in equation (32) results in a degeneration to a first order equation in F with a solution

$$F = \frac{\sigma_1^2 - \sigma_{12}^2}{\sigma_2^2 - \sigma_{12}^2} \qquad (33)$$

Substituting this expression for F in equation (33) back into equation (13) yields

$$\tan u = \frac{(\sigma_2^2 - \sigma_{12}^2)\sin\theta_1 + (\sigma_1^2 - \sigma_{12}^2)\sin\theta_2}{(\sigma_2^2 - \sigma_{12}^2)\cos\theta_1 + (\sigma_1^2 - \sigma_{12}^2)\cos\theta_2} \tag{34}$$

Note that if θ_1 and θ_2 are independent so that $\sigma_{12}^2 = 0$, then the weighting factor follows the familiar inverse variance law. The expression for σ_u^2 is given by equation (30) where C_{12} is defined by (31) and F is given by (33).

Now let v be a variable similar to u which is to be estimated from two modulo 2π angular measurements, θ_3 and θ_4. Then in a manner identical to that used for u we can find that

$$\tan v = \frac{\sin\theta_3 + G\sin\theta_4}{\cos\theta_3 + G\cos\theta_4}$$

$$= \frac{(\sigma_4^2 - \sigma_{34}^2)\sin\theta_3 + (\sigma_3^2 - \sigma_{34}^2)\sin\theta_4}{(\sigma_4^2 - \sigma_{34}^2)\cos\theta_3 + (\sigma_3^2 - \sigma_{34}^2)\cos\theta_4} \tag{35}$$

and

$$\sigma_v^2 = \left[(1 + GC_{34})^2\,\sigma_3^2 + G^2\,(G + C_{34})^2\,\sigma_4^2\right.$$

$$\left. + 2G\,(1 + GC_{34})(G + C_{34})\,\sigma_{34}^2\right]\left[1 + G^2 + 2GC_{34}\right]^{-2} \tag{36}$$

where

$$\sigma_3^2 = E\left[\Delta\theta_3^2\right] \tag{37a}$$

$$\sigma_4^2 = E\left[\Delta\theta_4^2\right] \tag{37b}$$

$$\sigma_{34}^2 = E\left[(\Delta\theta_3)(\Delta\theta_4)\right] \tag{37c}$$

$$C_{34} = \cos\,(\theta_4 - \theta_3) \tag{38}$$

$$G = \frac{\sigma_3^2 - \sigma_{34}^2}{\sigma_4^2 - \sigma_{34}^2} \tag{39}$$

A formula for $\sigma^2_{uv} = E\left[(\Delta u)(\Delta v)\right]$ will now be derived. From equations (13), (17), (20) and (21).

$$\Delta u = \frac{x\Delta y - y\Delta x}{x^2 + y^2}$$

$$= \frac{(\cos\theta_1 + F\cos\theta_2)(\cos\theta_1\,\Delta\theta_1 + F\cos\theta_2\Delta\theta_2)}{x^2 + y^2}$$

$$+ \frac{(\sin\theta_1 + F\sin\theta_2)(\sin\theta_1\Delta\theta_1 + F\sin\theta_2\Delta\theta_2)}{x^2 + y^2}$$

$$= \frac{(1 + FC_{12})\,\Delta\theta_1 + F\,(F + C_{12})\,\Delta\theta_2}{1 + 2FC_{12} + F^2} \tag{40}$$

Similarly

$$\Delta v = \frac{(1 + GC_{34})\,\Delta\theta_3 + G\,(G + C_{34})\,\Delta\theta_4}{1 + 2C_{34}\,G + G^2} \tag{41}$$

Then multiplying equation (40) by (41) and taking expected values we arrive at the cross variance expression

$$\sigma^2_{uv} = \frac{(1 + FC_{12})(1 + GC_{34})\,\sigma^2_{13} + G\,(G + C_{34})(1 + FC_{12})\,\sigma^2_{14}}{(1 + 2C_{12}\,F + F^2)(1 + 2C_{34}\,G + G^2)}$$

$$+ \frac{F\,(F + C_{12})(1 + GC_{34})\,\sigma^2_{23} + FG\,(F + C_{12})(G + C_{34})\,\sigma^2_{24}}{(1 + 2C_{12}\,F + F^2)(1 + 2C_{34}\,G + G^2)} \tag{42}$$

This discussion of this general phase estimation problem will now be applied to the Airborne OMEGA tracking filter design. The two variables corresponding to u and v at the time of the nth measurement are:

$$u \to \hat{\varphi}(n,n)$$

$$v \to \hat{\Delta\varphi}(n,n)\,\Delta t$$

The phase estimate is based upon the previous phase estimate time updated and the phase measurement obtained from the burst filter. The phase rate error estimate is based upon the previous phase rate error estimate time updated and the difference between the measured and estimated phase modified by the error in phase due to the phase rate error. Then the θ_i in the general problem correspond to:

$$\theta_1 \rightarrow \hat{\varphi}(n,n-1)$$

$$\theta_2 \rightarrow \varphi_m(n)$$

$$\theta_3 \rightarrow \Delta\hat{\dot{\varphi}}(n,n-1)\,\Delta t$$

$$\theta_4 \rightarrow \varphi_m(n) - \hat{\varphi}(n,n-1) + \Delta\hat{\dot{\varphi}}(n,n-1)\,\Delta t$$

Then the following correspondences can be made:

$$\sigma_u^2 \rightarrow \sigma_{\varphi\varphi}^2(n,n)$$

$$\sigma_v^2 \rightarrow \sigma_{\dot{\varphi}\dot{\varphi}}^2(n,n)$$

$$\sigma_{uv}^2 \rightarrow \sigma_{\varphi\dot{\varphi}}^2(n,n)$$

$$\sigma_1^2 \rightarrow \sigma_{\varphi\varphi}^2(n,n-1)$$

$$\sigma_2^2 \rightarrow \sigma_m^2(n)$$

$$\sigma_3^2 \rightarrow \sigma_{\dot{\varphi}\dot{\varphi}}^2(n,n-1)$$

$$\sigma_4^2 \rightarrow \sigma_m^2(n) + \sigma_{\varphi\varphi}^2(n,n-1) - 2\sigma_{\varphi\dot{\varphi}}^2(n,n-1) + \sigma_{\dot{\varphi}\dot{\varphi}}^2(n,n-1)$$

$$\sigma_{12}^2 \rightarrow 0$$

$$\sigma_{13}^2 \rightarrow \sigma_{\varphi\dot{\varphi}}^2(n,n-1)$$

$$\sigma_{14}^2 \rightarrow -\sigma_{\varphi\varphi}^2(n,n-1) + \sigma_{\varphi\dot{\varphi}}^2(n,n-1)$$

$$\sigma_{23}^2 \rightarrow 0$$

$$\sigma_{24}^2 \rightarrow \sigma_m^2(n)$$

$$\sigma_{34}^2 \rightarrow -\sigma_{\varphi\dot{\varphi}}^2(n,n-1) + \sigma_{\dot{\varphi}\dot{\varphi}}^2(n,n-1)$$

From equations (33) and (39)

$$F = \frac{\sigma^2_{\varphi\varphi}(n,n-1)}{\sigma^2_m(n)} \tag{43}$$

$$G = \frac{\sigma^2_{\varphi\dot{\varphi}}(n,n-1)}{\sigma^2_m(n) + \sigma^2_{\varphi\varphi}(n,n-1) - \sigma^2_{\varphi\dot{\varphi}}(n,n-1)} \tag{44}$$

From equations (31) and (38)

$$C_{12} = C_{34} = C = \cos(\varphi_m(n) - \hat{\varphi}(n,n-1)) \tag{45}$$

Using equations (13) and (35) the measurement update equations for the state variables φ and $\Delta\dot{\varphi}\Delta t$ are

$$\tan(\hat{\varphi}(n,n)) = \frac{\sin(\hat{\varphi}(n,n-1)) + F\sin(\varphi_m(n))}{\cos(\hat{\varphi}(n,n-1)) + F\cos(\varphi_m(n))} \tag{46}$$

$$\tan(\Delta\dot{\varphi}(n,n)\,\Delta t)$$

$$= \frac{\sin(\Delta\hat{\dot{\varphi}}(n,n-1)\,\Delta t) + G\sin(\varphi_m(n) - \hat{\varphi}(n,n-1) + \Delta\hat{\dot{\varphi}}(n,n-1)\,\Delta t)}{\cos(\Delta\hat{\dot{\varphi}}(n,n-1)\,\Delta t) + G\cos(\varphi_m(n) - \hat{\varphi}(n,n-1) + \Delta\hat{\dot{\varphi}}(n,n-1)\,\Delta t)} \tag{47}$$

Equations (30), (36) and (42) become

$$\sigma^2_{\varphi\varphi}(n,n) = \left[(1+FC)^2\,\sigma^2_{\varphi\varphi}(n,n-1) + F^2\,(F+C)^2\,\sigma^2_m(n)\right]\left[1 + 2CF + F^2\right]^{-2} \tag{48}$$

$$\begin{aligned}\sigma^2_{\varphi\dot{\varphi}}(n,n) = \Big[&(1+FC)(1+2CG+G^2)\,\sigma^2_{\varphi\dot{\varphi}}(n,n-1)\\ &- G\,(1+FC)(G+C)\,\sigma^2_{\varphi\varphi}(n,n-1)\\ &+ FG\,(F+C)(G+C)\,\sigma^2_m(n)\Big]\left[1+2CF+F^2\right]^{-1}\left[1+2CG+G^2\right]^{-1}\end{aligned} \tag{49}$$

$$\sigma^2_{\dot\varphi\dot\varphi}(n,n) = \left\{\left[1 + GC\right]^2 \sigma^2_{\dot\varphi\dot\varphi}(n,n-1) + G^2 \ (G+C)^2 \left[\sigma^2_m(n) + \sigma^2_{\varphi\varphi}(n,n-1) - 2\,\sigma^2_{\varphi\dot\varphi}(n,n-1) + \sigma^2_{\dot\varphi\dot\varphi}(n,n-1)\right] + 2G\ (1 + GC)(G+C)\left[\sigma^2_{\dot\varphi\dot\varphi}(n,n-1) - \sigma^2_{\varphi\dot\varphi}(n,n-1)\right]\right\} \left[1 + 2CG + G^2\right]^{-2} \tag{50}$$

Equations (48), (49), and (50) are the measurement update equations for the tracking filter covariance matrix.

Equations (46) and (47) can be put in a form which more conveniently shows the effect of the new measurement $\varphi_m(n)$ on the time updated estimates $\hat\varphi(n,n-1)$ and $\hat{\Delta\dot\varphi}(n,n-1)\,\Delta t$. Consider again the general estimation problem and the form of equation (13) repeated here

$$\tan u = \frac{\sin\theta_1 + F\sin\theta_2}{\cos\theta_1 + F\cos\theta_2} \tag{13}$$

From trigonometry

$$\tan(u-\theta_1) = \frac{\tan u - \tan\theta_1}{1 + \tan u \tan\theta_1} \tag{51}$$

Substituting (13) into (51) yields

$$\tan(u-\theta_1) = \frac{\dfrac{\sin\theta_1 + F\sin\theta_2}{\cos\theta_1 + F\cos\theta_2} - \dfrac{\sin\theta_1}{\cos\theta_1}}{1 + \dfrac{\sin\theta_1(\sin\theta_1 + F\sin\theta_2)}{\cos\theta_1(\cos\theta_1 + F\cos\theta_2)}}$$

$$= \frac{\cos\theta_1\sin\theta_1 + F\cos\theta_1\sin\theta_2 - \sin\theta_1\cos\theta_1 - F\sin\theta_1\cos\theta_2}{\cos^2\theta_1 + F\cos\theta_1\cos\theta_2 + \sin^2\theta_1 + F\sin\theta_1\sin\theta_2}$$

$$= \frac{F\sin(\theta_2 - \theta_1)}{1 + F\cos(\theta_2 - \theta_1)}$$

Applying this result to equations (46) and (47) using the same substitutions as before yields

$$\hat{\varphi}(n,n) = \hat{\varphi}(n,n-1) + \tan^{-1} \frac{\sigma^2_{\varphi\varphi}(n,n-1) \sin(\varphi_m(n) - \hat{\varphi}(n,n-1))}{\sigma^2_m(n) + \sigma^2_{\varphi\varphi}(n,n-1) \cos(\varphi_m(n) - \hat{\varphi}(n,n-1))} \tag{52}$$

$$\hat{\Delta\varphi}(n,n)\,\Delta t = \hat{\Delta\varphi}(n,n-1)\,\Delta t$$

$$+ \tan^{-1} \frac{\sigma^2_{\varphi\dot{\varphi}}(n,n-1) \sin(\varphi_m(n) - \hat{\varphi}(n,n-1))}{\sigma^2_{m1}(n) + \sigma^2_{\varphi\dot{\varphi}}(n,n-1) \cos(\varphi_m(n) - \hat{\varphi}(n,n-1))} \tag{53}$$

where $\sigma^2_{m1}(n) = \sigma^2_m(n) + \sigma^2_{\varphi\varphi}(n,n-1) - \sigma^2_{\varphi\dot{\varphi}}(n,n-1)$ (54)